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OF SUPERPLASTICALLY FORMED AND DIFFUSION
BONDED (SPF/DC) TITANIUM STRUCTURE TO
LAMINAR FLOW CONTROL (LFC) WING DESIGN
(Rockwell International Corp., Los Angeles)

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Study of the Application of Superplastically Formed and Diffusion Bonded (SPF DB) Titanium Structure to Laminar Flow Control (LFC) Wing Design

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16. Abstract A study was conducted to assess the application of Rockwell International's super-plastically formed and concurrently diffusion bonded (SPF/DB) titanium process to produce structure that is compatible with NASA's laminar flow control (LFC) concepts. The Lockheed LFC-200-R configuration, a 200 passenger, Mach 0.8 at 11600 meter (38000 feet) altitude, aircraft was selected as a baseline for the study. Eighteen design concepts for a LFC wing cover, using various SPF/DB approaches, were developed. After evaluation of producibility, compatibility with LFC requirements, structural efficiency and fatigue requirements, three candidates were selected for fabrication of 15x23 CM (6 x 9 in) demonstration panels. Included were both sand-wich and stiffened semi-sandwich panels with slotted and perforated surfaces. Subsequent to the evaluation of the three demonstration panels, one concept was selected for fabrication of a 0.3 x 1.0 meter (12 x 42 inch) feasibility panel. It was a stiffened, semi-sandwich panel with a slotted surface, designed to meet the requirements of the upper wing cover at the maximum wing bending moment of the base-line configuration. The panel was successfully completed, thereby demonstrating the applicability of the SPF/DB process to combine LFC features into primary wing structure.					
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STUDY OF THE APPLICATION OF SUPERPLASTICALLY
FORMED AND DIFFUSION BONDED (SPF/DB) TITANIUM STRUCTURES
TO LAMINAR FLOW CONTROL (LFC) WING DESIGN

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FOREWORD

This document is the final report for the "Study of the Application of Superplastically Formed and Diffusion Bonded (SPF/DB) Titanium Structures to Laminar Flow Control (LFC) Wing Structures Program," conducted by the Los Angeles Division of Rockwell International for NASA, Langley Research Center under Contract No. NAS1-14566. The NASA Technical Monitor for the program was Albert Kyser. The Rockwell personnel who participated in the program were:

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The program was initiated on August 11, 1976 and completed on December 15, 1978.

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STUDY OF THE APPLICATION OF SUPERPLASTICALLY
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TO LAMINAR FLOW CONTROL (LFC) WING DESIGN

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1.0 SUMMARY

A preliminary evaluation of the ability of Rockwell's Superplastically Formed/Diffusion Bonded (SPF/DB) titanium process to produce structure for NASA's Laminar Flow Wing (LFC) concepts has been conducted. The study has demonstrated that the process can produce LFC structure, making use of unique design and fabrication concepts unobtainable in any other manner.

Eighteen design concepts for an LFC cover, using various SPF/DB approaches, were developed. The three most favorable of these, based on producibility, compatibility with LFC requirements, structural efficiency and fatigue considerations, were selected for fabrication of 15 x 23 cm (6 x 9 inches) demonstration panels. These concepts were: semicircular, semisandwich with slotted surface; sine wave truss core sandwich with perforated surface; and hat-section semisandwich with slotted surface.

Based on both the experience gained in the fabrication of the demonstration panels and evaluation of additional factors such as weight, inspectability, and compatibility with substructure attachment, the hat-stiffened semisandwich design was selected for fabrication as a .30 x 1.0 m (12 x 42 inches) feasibility panel. The panel was successfully completed, thereby demonstrating the applicability of the SPF/DB process to LFC wing structure.

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2.0 INTRODUCTION

In 1973 the cost of fuel accounted for approximately 20 percent of the direct operating cost for a long range transport aircraft. Since then, fuel costs have increased out of proportion to other costs. At the present time, fuel costs account for approximately 45 percent of the direct operating costs. See reference 1. The continually increasing cost of the diminishing supply of fuel available, emphasizes the importance of improving the energy efficiency of long-range transport aircraft. A significant facet in the on-going effort to improve fuel economy is to reduce viscous drag through the application of laminar flow control (LFC).

An economically feasible LFC system requires aerodynamic surfaces that will remain smooth throughout the useful life of the aircraft. It also requires an involved system of internal ducting. A concurrent superplastic forming and diffusion bonded titanium process (SPF/DB), developed by Rockwell International, has the potential for producing airframe structure that will meet these requirements.

Titanium is a corrosion resistant material with a high strength to weight ratio that will be an excellent surface material. The SPF/DB process allows the LFC surface features and much of the internal ducting to be combined into the primary structure of the wing cover.

This report documents the initial effort to develop an LFC wing cover panel using the SPF/DB process. It includes establishing the design requirements and criteria; concept development through design and fabrication of panel specimens; as well as development and fabrication of a feasibility panel.

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3.0 BACKGROUND

The importance of maintaining Laminar Flow Control (LFC) for low fluid-flow friction has been recognized since 1904 when Prandtl first conducted his experiments in Germany. Although much was accomplished in the intervening years in advancing the transition from laminar to turbulent flow, the use of LFC to reduce drag was not extensively pursued until 1949 when Dr. W. Pfenninger began his work at Northrop Aircraft Company. This work, sponsored by NACA, led to the Air Force program in which Northrop designed, built and tested the X-21A airplane which incorporated a full LFC wing. Fabrication and flight experience with the X-21A wing demonstrated that the LFC feature shown in figure 1 can be integrated into an airframe structure with a relatively small penalty in weight.

The Northrop design employed an outer skin of .50 to .63 mm (.020 to .025 inch) aluminum alloy bonded to an aluminum honeycomb sandwich panel. Slots, 15 mm (.006 inch) in width, are cut in the outer skin in a spanwise direction. These slots connect to a 4.8 mm (.188 inch) plenums, premachined in the adhesive line, which is a minimum of .5 mm (.020 inch). Throttling holes were drilled through the honeycomb panel to form a passage to channels bonded to the inner surface of the panel. These channels distribute boundary layer air to cross ducts which transfer air to the pumps.

Although the LFC wing programs on the X-21A and other test aircraft have demonstrated the feasibility of the LFC concept, they have also served to identify a number of problems with current designs.

3.1 PROBLEMS

Corrosion.- For concepts employing aluminum alloy moldline surfaces, corrosion can have a disastrous effect on the suction slots. This is particularly severe where the slots are machined after panel fabrication, thus restricting the use of effective protective systems. Corrosion in the slots not only disturbs and restricts the airflow, but also will cause the slots to accumulate debris at a more rapid rate than clean slots.

Designs employing aluminum honeycomb core are also faced with a corrosion problem. On military aircraft, maintenance of this material has been so expensive that aluminum honeycomb is seldom used for primary structure. In cases where existing installations require replacement, other types of structure are frequently substituted in spite of increased weights.

Erosion.- The high velocity air with entrained dust, grit and ice particles can present a severe erosion problem to exposed edges, particularly of softer materials. Composite materials, employing Kevlar, fiberglass or graphite fibers in a resin matrix are particularly susceptible because of the soft matrix material which erodes away leaving the fibers exposed to the air stream. These loose fibers will tend to block the air passages in addition to trapping additional debris, further restricting the flow.

Structural Inefficiency.- Structural inefficiency results from three design approaches currently being considered for LFC wing structures. The first arises from the use of the LFC panel as a parasitic surface which does not carry primary structural loads. Thus, the suction surface, its support structure and the internal ducting must be considered as secondary structure forcing the substructure to react the wing bending and torsion loads. Since this primary structure may be as much as two inches below the wing moldline, its efficiency is further reduced because it cannot take advantage of the full depth of the wing.

The second inefficiency in the current design is found in the choice of materials. Although graphite/epoxy exhibits high structural efficiency when properly used, it suffers a large loss in static load carrying ability when holes, added for boundary layer air metering, cut through the graphite fibers. Aluminum alloy, under either static or fatigue loading, demonstrates lower structural efficiency than titanium. This condition remains unchanged for a wide range of K_t (stress concentration values).

The use of adhesives to join the elements of the LFC panels also contributes to the structural inefficiency of current systems. The weight of the adhesive, the low shear allowable, and the degradation when exposed to moisture and fuel all are factors which tend to cause the weight of bonded structures to exceed that of integral structure.

Cost.- Certainly the most critical factor in the success of an LFC airplane is the cost increment, both initial cost and life cycle cost, imposed by the LFC system. This includes not only the pumping system which provides the suction, but also the provisions for air flow in the wing covers as well. These provisions, in addition to reducing the structural efficiency, add significantly to the cost of the structure on existing designs. Based on the X-21A wing design, Northrop has estimated (reference 2) that the airframe cost will increase by 13 percent with the incorporation of LFC provisions. Since this increase is primarily in the wing cost, which is historically about 15 percent of the total airframe cost, the effect on wing cost would be an increase of approximately 70 percent. In a recent study by the Boeing Company (reference 3), the cost of the wing structure increased by 100 percent with the addition of LFC requirements. Boeing estimates that the increased cost is due primarily to the added complexity of the LFC provisions, rather than the use of composite structure.

Submitted by: [illegible]

Other Problems.- In addition to the above, LFC designs face the problems of: clogging by insects, dust and ice crystals; repairing and maintaining suction surfaces and the pumping systems; and providing a fail-safe system.

3.2 A POTENTIAL SOLUTION: SPF/DB TITANIUM

Although no single technology breakthrough can offer the solution to all of these problems, an emerging advanced titanium process does offer the potential of eliminating the corrosion and erosion problem while increasing structural efficiency. This process is superplastic forming with concurrent diffusion bonding (SPF/DB) of titanium.

Superplasticity in titanium is a phenomenon in which very large tensile elongations may be realized because, under the proper conditions of temperature and strain rate, local thinning (necking) does not occur. Diffusion bonding (DB) is the joining of titanium under pressure at elevated temperature without melting or use of bonding agents. Fortunately, DB of titanium is accomplished under conditions which are identical to those required for superplastic forming (SPF). This is the basis for the combined SPF/DB process. The combining of SPF/DB, the use of stop-off in selected areas to prevent bonding, and the use of argon gas to expand the diffusion-bonded parts provides a wide range of structural shapes, from simple two-sheet construction to extremely complex three-sheet sandwich structure. A detailed description of the process appears in the appendix.

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4.0 OUTLINE OF THE PROGRAM

OBJECTIVE

The objective of this program is to investigate the application of SPF/DB to a laminar flow wing panel section. This objective consists of two parts:

1. To analytically determine the applicability of the SPF/DB process to LFC wing structures.
2. To demonstrate the feasibility of the study results by fabricating a 0.3 x 1.0 meter (12 x 42 inch) demonstration panel.

OUTLINE OF TASKS

To meet the objective, the program was conducted in three tasks:

- Task I Design Requirements and Criteria
- Task II Concept Development and Design
- Task III Feasibility Panel Fabrication

Brief descriptions of the approach used in these tasks is presented in the following paragraphs.

TASK I - DESIGN REQUIREMENTS AND CRITERIA

Baseline data required to perform the concept development task were produced in this task. They were based on a review of previous designs and data developed for LFC wings, particularly the X-21 fabricated by the Northrop Corporation. The data was obtained from various company and governmental sources and include previous LFC techniques and methods, structural requirements, and cost and manufacturing data.

Design requirements and criteria for structural concepts development were established. The design loads are representative of the loads which would occur at the wing station of maximum bending moment on an aircraft sized to carry 200 passengers for a range of 10,000 Km (5500 n. miles) at a cruise Mach number of 0.8. Manufacturing tolerances were defined for the following considerations.

- (1) required surface smoothness,
- (2) spanwise and chordwise surface waviness limits,
- (3) step and gap limits at panel splices and interior access joints.

The effect of internal holes on fatigue life was evaluated.

Representative airflow requirements including slot widths and spacing, plenum chamber, widths and depths, and throttling and transfer duct requirements using the results of the Lockheed System Study (NAS1-13694) were determined. See reference 4.

Upon completion of this task, the established design requirements and criteria were reviewed with NASA for concurrence.

TASK II - CONCEPT DEVELOPMENT AND DESIGN

Using the criteria established above, design concepts were developed which employed SPF/DB titanium construction. A total of 18 design concepts were developed including both sandwich panels and stiffened skin concepts. These designs were evaluated and the three most promising designs selected for further development.

After NASA approval of the three selected concepts, design drawings were prepared. The drawings provided sufficient detail so that research laboratory technicians could fabricate 15 x 23 cm (6 x 9 in.) panels for process development and evaluation.

Following design of the three titanium laminar flow wing panel concepts, demonstration on a laboratory basis was accomplished. Subscale panels of each of the three designs were fabricated. The parts were 15 x 23 cm (6 x 9 inch) with full-depth cross sections. Existing steel tooling was utilized for the panel bonding and forming. Special inserts to control the internal plenum chambers were machined as required. SPF/DB process parameters, stop-off application materials and methods and preparation of the titanium sheet were based on past experience and applied to the three design concepts. Although subscale in size, all laboratory parts were laid up and processed similar to full scale processing in order to determine potential problem areas and to lay the foundation for full-scale layup. All subscale parts were evaluated destructively and nondestructively to determine the selection of optimum process variables and techniques.

TASK III - FEASIBILITY PANEL FABRICATION

After evaluation of the three subscale panels, the most promising design was selected for scale-up to a larger panel. A new drawing was prepared for the fabrication of the 30 x 100 cm (12 x 42 inch) panel, incorporating the lessons learned from the subscale panel development. The full-scale panel was fabricated in a production environment, but with laboratory control. The panel had a surface radius of curvature of approximately 12 m (40 ft.).

Stainless steel tooling with the desired configuration was fabricated to accomplish the panel manufacture. The tooling consisted of a top plate and a self-contained bottom plate. A seal projection was placed on the bottom plate in which inlet and outlet argon gas tubes were provided. The titanium sheet was cleaned, the gas tubes installed, the stop-off pattern applied and the entire pack placed between heating platens and heated to 926° C (1700° F) in a production hydraulic press.

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5.1 CONFIGURATION

5.2 SURFACE SMOOTHNESS CRITERIA

For flight conditions of Mach 0.8 and 16,600 meters (3800 ft.) altitude and a 4.6 meter (15 ft.) wing chord, the surface discontinuities must be kept below these values. Skin laps should be avoided, and if butt joints cannot be flush, it is better to have them step up instead of step down with respect to relative wind. Fasteners at main structural joints should not protrude above the outer skin. Panels should be formed with the field waviness (total amplitude divided by wave length) to less than $1/3000$; and the joint design should limit the waviness at these points to $1/1000$. These waviness criteria are predictions that need to be verified by testing of large chord specimens.

5.3 DUCT REQUIREMENTS

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6.4 mm (0.25 inch), 3.0 meters (10 ft.) in from the tip to 36.0 mm (1.4 inch) at the critical region of the planform break. These figures are based on the assumption that all the boundary layer air collected is ducted from tip to the inboard sweep break between the sandwich skins. This is a conservative approach since in all probability, cross ducting would be installed at 6.0 to 9.0 meters (20 to 30 feet) intervals to reduce the structural problems which would be associated with transferring the entire volume of air at one location.

5.4 LFC CRITERIA

In the course of investigations concerning the failure to maintain laminar flow at the highest Reynolds numbers on the X-21 aircraft, a laboratory investigation of flow in the suction slots revealed that when the slot Reynolds number exceeded 100, disturbances were generated in the slots. This criterion is now believed to be a good one for setting maximum slot spacing.

The slot Reynolds number is the product of slot velocity and slot width divided by the kinematic viscosity. Setting this equal to 100 and solving for maximum slot spacing yields:

Slot spacing in mm equals 30,480

$$\frac{U}{\nu} \cdot C_Q$$

where U = flight velocity

ν = kinematic viscosity

$$C_Q = \frac{\text{average suction velocity}}{\text{free stream velocity}}$$

The baseline aircraft is designed to fly at 11,600 meters (38,000 ft.) at 0.8 Mach number. This gives a Reynolds number per meter of 5.6 million (per foot of 1.72 million). The values of C_Q in the same study in the structural box area range from 1 to 2 times 10^{-4} . The maximum slot spacing comes out at 177.8 mm (7 inches) for the lighter suction value and 88.9 mm (3.5 inches) for the heavier suction value.

The recommended slot width, plenum dimensions and metering hole sizes and spacing shown in figure 4 are based on X-21A experience.

For designs employing a perforated surface, the dimensional requirements are shown in figure 5. These data are based on X-21A data and recommendations by Dr. Werner Pfenninger of NASA LRC.

5.5 STRUCTURAL REQUIREMENTS

The wing static load requirements (table 1) are based on data developed by Lockheed for the LFC-200-R configuration. As specified in the contract, the design point used for the cover designs in this program is the section subjected to the maximum bending moment. As shown in the table, this occurs at B. P. 3.99 meters (157 inches) where the moment is 8.7 million newton-meters (77 million inch-pounds) limit. This produces an ultimate unit compression load (Nx) of 4,240,000.0 newtons per meter (24,200 pounds per inch) on the upper cover.

5.6 FATIGUE CRITERIA

A simplified fatigue spectrum based on typical commercial air transport usage is shown in figure 6. It consists of one ground-air-ground (G-A-G) cycle and 60 average gust/maneuver cycles per flight. The G-A-G cycle varies from $-2/3g$, $-1.38 \times 10^8 \text{ N/M}^2$ (-20,000 psi) to $+1 \frac{1}{3}g$, $2.76 \times 10^8 \text{ N/M}^2$ (40,000 psi). The 60 gust/maneuver cycles consist of 20 cycles at $1g + 1/5g$, 1.65×10^8 - $2.48 \times 10^8 \text{ N/M}^2$ (24,000-36,000 psi) and 40 cycles at $1g + 1/10g$, 1.86×10^8 - $2.28 \times 10^8 \text{ N/M}^2$ (27,000-33,000 psi) stress. Stress concentration factors for the critical design features have been obtained from Peterson's "Stress Concentration Factors," and the Rockwell Fatigue Manual. These are listed below:

LFC slot sides - $K_t = 1.2$,

LFC slot ends - $K_t = 2.0$

LFC perforations (round hole) - $K_t = 3$,

Canted (45°) LFC metering holes - $K_t = 3$ and

Elongated hole in corrugated shear web - $K_t = 6$.

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6.0 DEVELOPMENT OF SPF/DB PANEL DESIGNS

6.1 OPTIMIZATION METHOD

The optimization of the wing cover concepts were conducted in two stages. First, the general structural arrangement was optimized, and evaluated. This was followed by a detailed optimization of the individual cover concepts being developed.

The general structural arrangement was optimized by investigating both multi-spar and multi-rib wings. In each case a number of different spar and rib spacings were checked at four wing stations to determine the weight trends. The wing cover structure was sized from charts (figures 7 and 8) developed at Rockwell using the methods reported in reference 5. The spar structure weights were based on the optimization curves shown in figure 8 which was developed at Rockwell for an earlier study (reference 6).

The multi-spar wing design was investigated to determine the wing cover requirements using the truss core sandwich curve on the "Compression Panel" chart shown in figure 6. The spars were sized for the crushing load and shear using the "Optimization Curves" in figure 9.

The multi-rib wing design outer cover size was determined from the "Wide Column Configuration" chart, figure 8, using the truss core semi-sandwich curve, which shows a slight improvement in efficiency over sandwich for this type of structure. The ribs were sized by calculating the rib crushing load and using this to determine the strength requirement. A check was then made to determine whether the strength sizing requirement provided adequate stiffness. The spars for the multi-rib wing were sized for the wing shear only since the ribs were sized to react the crushing loads.

$\bar{t}$ is the average equivalent thickness of the material in a structural element and is used as a weight index. The $\bar{t}$ for the total wing structure, i.e., $\bar{t}_{total}$, was determined by converting the substructure, spar and rib structural requirements into equivalent $\bar{t}$ and adding them to the wing cover $\bar{t}$. The $\bar{t}_{totals}$ were plotted against rib and spar spacing to indicate weight trends as shown in figure 10.

These curves show that for multi-rib design, the optimum spacing is approximately .50 meters (20 inches). For a multi-spar design, the optimum spacing is approximately .64 meters (25 inches). These designs are shown in figure 11.

The $\bar{t}_{total}$ structural areas required for both the multi-rib and the multi-spar designs shown in figure 11, were calculated at four spanwise locations and plotted in figure 12. As shown in the figure, the area (or weight) for the two concepts are within 10 percent.

The absence of intermediate spars in the multi-rib wing simplifies the chordwise ducting for carrying LFC air, compared to the multi-spar design where the ducting must penetrate each of the intermediate spars. This factor was judged to be more important to a practical wing design than the weight difference, consequently, the multi-rib design was selected for the study.

6.2 DESIGN CONCEPTS

Using the selected design criteria described above, 18 LFC wing cover concepts were designed and evaluated. Concept development and sizing was assisted by the parametric curves and equations presented in Emero and Spunt's "Wing Box Optimization Multi-Rib and Multi-Web Wing Box Structures Under Combined Shear and Bending," (reference 5). Figure 13 shows typical optimization relationships used for the multi-rib cover designs. The design shown in figures 14 through 31, which are described below, were evaluated for:

- a. Producibility
- b. Compatibility with LFC requirements
- c. Structural efficiency
- d. Fatigue considerations

As a result of this evaluation, the panels recommended for Task II, fabrication are:

- a. Concept D, shown in figure 17
- b. Concept J, shown in figure 24
- c. Concept N, shown in figure 28

On all designs, the moldline slots or perforations are to be machined after panel forming. An evaluation of the 18 designs and the rationale for the recommended concepts is given in the following paragraphs.

Concept A - Figure 14

This design is an integral LFC surface/structural panel in which the LFC ducting and the wing load-carrying elements are combined into a single structure. This concept is a truss-core sandwich with moldline slots which introduce the LFC air into small plenums which meter the flow through discrete holes into the interior of the sandwich. The plenums are formed by use of a steel insert which is removed after SPF/DB of the panel.

This design, to maintain maximum structural efficiency, requires the thickness of the truss core to be approximately 80 percent of the face sheets. This ratio will not allow proper expansion of the core without face sheet creasing. The method used to prevent this is to use thick face sheets and chem-mill them after sandwich expansion, adding to the cost of fabrication.

Concept B - Figure 15

The unique feature of this design is the method of producing the slot plenum chamber. This is accomplished by using the core sheet to pull the inner face sheet away from the outer face sheet during the core expansion process. Although this concept will work in theory, the development time and cost to reduce it to practice appears prohibitive.

Concept C - Figure 16

Evaluation of this design revealed that the large unsupported span of outer skin will buckle. It was rejected for this reason.

Concept D - Figure 17

A design which avoids the costs associated with the relatively heavy gage core of Concept A is shown in figure 17. Sine wave truss core is used on this design to replace the straight truss core. Because of the built-in sine waves, the core will not carry axial loads while retaining its face sheet stabilizing properties and its shear capabilities. These loads will allow the use of thin gage core, eliminating the need for extra thickness on the face sheet to prevent creasing. This feature will make Concept D the lowest cost of the sandwich concepts studied, and for this reason, was recommended for fabrication. Perforations on the moldline surface are shown on this concept as an alternate to the slots.

Concept E - Figure 18

This dimple core design will be advantageous for panels with isotropic loading conditions. Since the LFC wing studied is a high-aspect ratio structure with predominantly spanwise loads, this design would probably be less efficient than truss-core sandwich.

Concept F - Figure 19

The purpose of this design is to provide more control of the boundary layer air metering after it leaves the moldline plenum. Producibility of this panel is doubtful.

Concept G - Figure 20

This concept was designed to allow the inner skin to be expanded without constraint by a die. Its main advantages are low cost tooling and uniform thickness of the inner skin. However, preliminary laboratory trials showed severe creasing of the outer skin.

Concept H - Figure 21

The problem encountered with Concept G is avoided with this design by the use of tooling which will limit the movement of the inner skin, thus preventing it from producing creases on the outer skin. As shown in figure 22, this will also allow the slot plenum to be formed without inserts, a high cost feature of Concept G. As the inner sheet is being expanded, it pulls away from the moldline sheet forming the plenum. Even though the semicircular inner skin is expanded against the tooling, it is expected to form to a uniform gage as was the experience with Concept G.

This design also is superior to the majority of the previous designs because of the smoother air flow in the semicircular ducts. As with the other semisandwich designs, ducting air to the cross-ducts should present less problems than the full sandwich designs.

Concept I - Figure 23

To provide for shear attachments to the moldline skin, Concept H has been modified by spreading the semicircular stiffeners apart. The efficiency of the panel has been slightly improved by the use of a thinner inner skin with a reinforcing pad bonded to its lower surface.

Concept J - Figure 24

A simplification of Concept I is shown in figure 24. The separate reinforcing pad in Concept I has been eliminated by the use of a heavier gage inner skin. Although this results in a seven percent weight increase, the accompanying cost reduction was significant in selecting this design for fabrication.

Concept K - Figure 25

The design, shown in figure 25 is a variation of the semisandwich Concepts G through J, with triangular corrugations in lieu of the semicircular stiffening elements. The plenums on this design, as in Concept I, are formed by the expansion of the inner sheet.

Concept L - Figure 26

Another variation of Concept K with a perforated outer skin instead of slotted is shown here. Producibility of this arrangement is beyond current technology.

Concept M - Figure 27

A variation of Concept K, but with higher structural efficiency, is shown in figure 27. This design would be adequate for structures where the shear loads to be transferred from the ribs to the skin are low.

Concept N - Figure 28

A variation of the hat-stiffened sheet concept of figure 27 is shown in figure 28. Two modifications have been made: (1) The hats have been spread apart so that a shear attachment to the outer skin can be accommodated; and (2) Reinforcing pads have been added to the inner cap of the hats, thus reducing the inner skin gage. This reduces the weight of the section approximately 20 percent. This design was selected for fabrication.

Concept O - Figure 29

This design is intended to offer a method of fabricating a semi-sandwich panel with simple tooling. The truss core sections are intended to produce the slot plenum during forming. The producibility of this concept has been judged to be beyond the state-of-the-art.

Concept P - Figure 30

Although this design has the highest structural efficiency of any proposed, two other drawbacks eliminate it. The collector ducts are too small and the cost of fabrication will be excessive.

Concept Q - Figure 31

A design employing slots spaced at 152.4 mm (6 inches) is shown here. The structural efficiency of this arrangement will be low.

6.3 DEMONSTRATION PANELS

6.3.1 CONCEPT SELECTION

After additional optimization work on the original designs, the following three design concepts for Task II fabrication were selected.

1. The sine wave truss core design shown on figure 32 is the same as Concept D, but shown in greater detail. Perforations for removing the boundary layer air have been selected for this design so that a comparison of the manufacturing costs can be made with the slots shown on the other two demonstration concepts. This panel design allows usage of very thin .65 mm (.025 inch) core since the sine wave shape stabilizes it. While this core will not carry axial load, it does stabilize the face sheets and will carry shear. Since the core is thin, it will reduce cost of fabrication. The $\bar{t}$ (unit area per unit length of chord) will be 7.04 mm (.277 inch), which is larger than the other two designs due to the inability of the core to carry axial load.
2. Figure 33 shows additional detail for the semicircular, semisandwich panel design shown in figure 24. The configuration contains provisions for rib chordwise shear attachments to the skin and has been optimized to provide the most efficient cross section. The $\bar{t}$ of the section is 6.25 mm (.246 inch) theoretical, but practical considerations increase it to 6.65 mm (.262 inch).

This design was selected over an alternate arrangement in which a reinforcement pad is bonded to the semicircular corrugation to produce a more efficient bending section. Although the $\bar{t}$ of the section is 5.82 mm (.229 inch), a seven percent weight saving over the selected design, it was decided that this savings was not worth the extra cost of adding the reinforcing pad. Figure 35 shows the variables used for this comparison and the results are shown in table 2.

3. The hat section semisandwich panel shown in figure 34 is similar to Concept N shown in greater detail. As shown in table 2, the hat-stiffened design with a reinforcing cap and hats spaced on 3-1/2 inch centers is 20 percent lighter than without the cap. Although the dimensions established for this study are valid for comparison, they do not represent the absolute optimum design. The material thicknesses have been further optimized to increase the efficiency of the section. Space between the stiffeners has been retained for rib chordwise shear attachment to the skin. The $\bar{t}$ is 6.22 mm (.245 inch).

6.3.2 FATIGUE ANALYSIS

A fatigue evaluation of the three selected design concepts shows that all concepts will provide adequate fatigue life in excess of 100,000 hours, which includes a scatter factor of two.

The corrugated webs of the truss core sandwich will pick up only nominal axial load, and will only be lightly loaded in shear, the $K_t = 6$ of the elongated hole in the web will not be the critical fatigue feature of this concept. Since all concepts have the 45° canted LFC metering holes, the $K_t = 3$ for this feature is critical, and all concepts will have the same fatigue life. A Rockwell International computer program designed to perform a parametric study of fatigue damage was used to calculate that for a $K_t = 3$ and the basic spectrum above, the concepts will have a fatigue life of 50,500 cycles or 2.02 lives (figure 36), which is acceptable in view of the conservative level of the assumed lg stress level. It is recognized that the K_t value at the joints will be greater than 3, but the panel thicknesses will be increased locally to reduce the stress level so that an acceptable fatigue life is reached.

6.3.3 FABRICATION

An important consideration in the assembly of the titanium sheet metal detail was the application of stop-off material to those areas of the diaphragm which are not to be bonded. Boron nitride was used as a stop-off material, which is mixed with a suitable binder and applied by the silk-screen technique. The stop-off slurry must, of necessity, be of a specific consistency and able to retain wetness. Dimensional accuracy was maintained by use of this application method through proper locating points.

The titanium sheet material for the face sheet and the core was in accordance with MIL specifications or Rockwell requirements with the added requirement of small grain size and no blocky or acicular alpha to insure superplasticity. The titanium sheets were typically prepared by sizing, notching, drilling or machining prior to cleaning and installing the gas tubes and applying the stop-off pattern.

All the concepts required the layup of a number of titanium sheets. This setup incorporated the holes necessary for air flow and the stop-off pattern for a stiffened skin structure. Fabrication entailed using a solid top sheet with the slots or perforations being added after bonding and forming. All sheets were laid up in the flat condition. Gas pressure bonding was accomplished from the bottom sheet side against the upper die inner cavity. After gas bonding of the selected areas for the panel was completed, superplastic expansion into the lower die cavity was then accomplished.

After removal from the die, the panels were chem-milled to final thicknesses. The closed ends of the panels were trimmed. The moldline slots or perforations were then added. Subsequent to processing, the panels were examined visually and X-ray inspected to verify core forming and internal bonding.

Forming Sandwich Concepts-- The initial trial in the development of the demonstration panel was the truss core sandwich panel design shown in figure 15. The purpose of this demonstration was to determine the feasibility of forming the micro-plumbing during the SPF/DB cycle as well as develop the pressure-temperature cycle for this configuration. The panel was successfully expanded and the steel inserts were withdrawn with a minimum of effort forming the slot-plenum shown in figure 37. However, slight creasing was experienced on the face sheets at the truss core nodes. Subsequent trials (figures 38 and 39) decreased the depth of creasing on the moldline surface so that a flush surface could be obtained by a minimum of cleanup machining. Although the creases on the inner face of the sandwich were not entirely eliminated, it is not felt to be a significant problem since other panels produced by Rockwell have eliminated the creasing.

The next set of trial panels were formed to develop the sine wave truss core design which was one of the concepts selected for a demonstration panel. It was expected that the thin core gage, .64 mm (.025 inch), would not pull creases in the face sheet. However, as figure 40 shows, slight creasing still occurred. Modifications of the time/pressure cycle on a second panel were made to eliminate the creases and were successful, as shown in figure 41.

Forming Semi-Sandwich Panels - The first semisandwich trial concept was a semicircular corrugation stiffened design shown in figure 21. The panel was free formed in a die which did not control the shape of the corrugations. The panel formed successfully (figure 42) with the inner skin expanding to a constant thickness. However, as shown in figure 43, the face sheet was pulled away from the moldline by the expansion of the inner skin. To correct this problem, a second panel was made using tooling which controlled the inner contour, thus eliminating the moldline deviation. The panel included a modification to the plenum shown in figure 22, which eliminated the steel insert used for the previous panels. On this trial the moldline surface was satisfactory and the plenum formed as predicted (figure 44) validating the concept. The same tooling concept was used to produce the design selected (figure 24) for the demonstration panel which formed as predicted (figure 45).

The third panel concept selected for demonstration was the hat-stiffened design shown in figure 28. Although this design involved additional complications because of the inner cap reinforcements, the first trial produced a satisfactory panel as shown in figure 46.

6.3.4 SUCTION SURFACE MACHINING

Panel Slotting - Several methods for producing the .20 mm (.008 inch) mold-line slots used for boundary layer air removal were investigated.

1. Mechanical saws
2. Electrical discharge machining (EDM)
3. Laser cutting
4. Electron beam cutting
5. SPF/DB

Mechanical Saw - The mechanical saw method employs a two inch diameter circular saw blade mounted on a milling machine. This method was used to slot the hat-stiffened panel producing clean slots, within tolerance. Cutter breakage during the slotting caused a minor amount of damage to the slots. The cost of this method is relatively low because of the simple setup required and the low cost cutters used. However, because of the frequent cutter breakage, the method is not recommended for production until cutter life can be improved.

Electrical Discharge Machining (EDM) - Two EDM methods were investigated. The first used a copper wire for an anode. Although the trial slots were satisfactory, the cutting rate was slow and the present limitation on slot length is three inches.

The use of copper sheet anode for EDM slotting proved to be superior. This method, which was used to slot one of the semicircular corrugation stiffened panels, produced clean, acceptable slots at low cost. The machining speed was comparable with mechanical slotting.

Laser Cutting - Laser cutting for laboratory size specimens was prohibitively expensive. Sample cuts appear clean on the moldline surface (figure 47), but on the inner surface the slots are unacceptably rough (figure 48). For the SPF/DB where the slotting is accomplished after panel forming and bonding, cleanup of the rough slot edges would be impossible, making this method unacceptable.

Electron Beam - Electron beam slotting of titanium sheet was investigated by Farrel Corporation for this program. After several trials, Farrel concluded that the process could not readily be adapted to this application without additional development.

SPF/DB Process Slot Formation - One slotting method which is still in the conceptual stage is the production of slots during the SPF/DB cycle. The slots might be produced by spacing outer moldline sheets one slot-width

apart, then bonding them to the substructure during the cycle. The development of tooling and processes required to produce slots in this manner is beyond the scope of this program.

Perforating the Panels - Making use of earlier experience, the Farrell Corporation, using an electron beam process, has demonstrated the capability of producing small diameter perforations, closely spaced and at high speed. After a minimum of development work to adapt the process to the titanium sheet gage used for the Rockwell panel, the sine wave demonstration panel was perforated with a .13 mm (.005 inch) diameter hole at .51 mm (.020 inch) spacing. Although some problems were experienced with complete perforating and with indexing the holes, the panel confirmed the feasibility of producing the hole pattern. The holes were the proper diameter on the inside surface (figure 49), but exhibited an eight degree half-cone angle, producing .25 mm (.010 inch) diameter holes on the moldline surface of the sheet (figure 50). The outer edge of the holes also exhibited an irregular surface which could not be removed by simple ultrasonic cleaning methods. This hole condition makes the electron beam method of producing perforations questionably acceptable for this type of panel.

6.3.5 COMPARISON OF DEMONSTRATION CONCEPTS

The three concepts selected for fabrication as demonstration panels all proved to be within current technology capabilities. The selection of the concept for a larger feasibility panel was based on a comparison of the features of all three concepts. Figure 51 summarizes this comparison.

Area and Weight - The hat-stiffened concept offers the minimum weight with the semicircular corrugated panel 7 percent heavier and the sandwich panel 13 percent heavier.

Production Cost - The semicircular corrugated panel will be lowest in cost because it requires the fewest number of details which must be processed before forming and because of the low-cost method of forming the plenum chamber. Although it requires additional detail parts (the reinforcing caps), the hat stiffened panel is second in cost ranking due to the low-cost method of forming the plenum chamber. The highest cost is the sandwich because of the extra complication of using a steel insert to form the plenum, then removing the insert after the SPF/DB cycle.

Visual Inspection - Both semisandwich panels can be readily inspected for cracks or other types of damage on all surfaces, except for very localized areas on the plenums. The sandwich, however, can only be visually inspected on the inner and outer face sheets. The core and inner sheet of the plenum will require X-ray for inspection.

Maintenance - Two types of maintenance have been considered: Cleaning the surface openings; and repair of damage (based on preliminary definition of repair techniques currently being developed). The slots on the semi-sandwich panels should require less frequent cleaning and be easier to clean than the perforations, according to studies by the Boeing Company. See reference 3.

Air-Load Rib Attachment - Air load ribs are relatively lightly loaded members which react the wing crushing loads, transfer air loads from the covers to the spars, and prevent general panel instability. For the hat-section cover design, these ribs can be attached directly to the inner caps of the hats allowing the ribs to be simple channels with caps parallel to the wing mold-line. This same type of rib can also be used with the sandwich design, with the rib cap attached directly to the inner face sheet. However, for the semi-circular corrugation design, the ribs must tie directly to the moldline skin, requiring a rib cap which is either scalloped or a rib cap parallel to the skin with individual shear clips attached to the skin between corrugations. This requires a heavier, more expensive rib than the hat-stiffened panel or the sandwich panel.

Panel Splice - A preliminary investigation into methods of splicing the three panel designs shows that welded joints offer the lowest weight, most leak-proof splice. The flat elements of the hat-stiffened design make it the simplest structure to join. Splicing the core of the sandwich panel requires local doublers and closeouts, making it the most complicated joint of the three designs.

Tailorable Geometry - One of the aspects of a realistic wing design which should be considered is the method of varying the cross sectional area of the cover to match the load variation. For the three designs evaluated, the hat-stiffened panel can be most easily tapered by varying the thickness of the pad on the inner surface of the hat. For the other designs, area variation must be accomplished by step-tapering the basic material thickness after forming, a more costly process.

Duct Area - To serve effectively as an LFC panel, the concept must provide sufficient enclosed area to collect and transfer the boundary layer air to the cross ducts. For cross ducting spliced at 10.7 meter (35 feet) intervals, the area required per chordwise unit of panel to maintain duct velocity below 10 percent of flight velocity is .00045 square meters (0.7 square inches). All the panels considered provide more area than this requirement.

6.3.6 FINAL SELECTION

Based on this comparison, the hat-stiffened panel shown in figure 52 was selected as the concept for the .30 by 1.0 meter (12 x 42 inch) feasibility panel.

6.4 FEASIBILITY PANEL

Before fabrication of the .30 x 1.0 meter (12 x 42 inches) feasibility panel, the design was optimized to be in compliance with the criteria in Section 5.0. The final dimensions were established and a detail drawing was prepared. Tooling was fabricated and several producibility specimens were made before the final panel was formed.

6.4.1 DESIGN OPTIMIZATION

Prior to preparing the detail drawing of the selected configuration for the feasibility panel, a more detailed optimization of the cross section geometry was conducted. Although the weight optimization, shown on table 2, was adequate for a preliminary screening, it was felt that additional refinement could produce an even lower weight section.

The approach in this optimization was to obtain such distribution of material throughout the section that the local and general instability modes of failure occur simultaneously and at the highest possible applied stress.

The section shown in figure 52 with sizes adequate to meet the constraints for design (strength, stiffness, temperature, assembly, etc) and production (slope of sides, distribution of material imposed by the superplastic formed process, minimum gages, etc.) was used as a starting point.

The section was optimized using an iterative process which considered:

- ° Section properties
- ° Distance between the neutral axis and the section centerline
- ° General instability allowable stress
- ° Local instability allowable stress for the appropriate elements of the section
- ° Applied stress
- ° $\bar{t}$ (as a weight comparison criterion)

Successive iterations were performed to improve the section properties for a higher local and general instability value, higher applied stress and lower weight, using the following general guidelines.

- ° A local instability allowable lower than the applied stress required a reduction in b/t of the element.

- A general instability allowable lower than the applied stress requires added material at upper or lower side or an increase of the section height.
- A neutral axis far from the centerline indicates non-efficient use of material for general instability failure mode.
- A low applied stress value indicates that the material is not used efficiently (maybe as a result of section type limitations).

With every change, the broad simultaneous effects on local and general instability allowables and on applied stress, location of neutral axis and weight factor (t), were considered. The iteration process was completed when general and local instability stresses were equal to or greater than the applied stress (within 1 percent).

Figure 53 shows the final optimized section.

6.4.2 DETAIL DESIGN

The idealized section shown in figure 53 was analyzed for producibility by the SPF/DB process, resulting in the following modifications:

- The inner cap reinforcement was tapered to permit easier removal from the forming tool.
- Methods were developed to predict and control the thinning of the tapered webs of the hat sections, which were formed from a constant thickness sheet. Control of thinning was necessary to ensure that the remaining thickness met the design optimization requirements described in Section 6.4.1.
- Taper was added to the hat section face sheet interface to reduce stress concentration at the interface.
- The internal plenums, metering holes and moldline slots were added.

These revisions were then incorporated into the detail feasibility panel drawing shown in figure 54. This drawing shows the overall size of the panel .30 x 1.0 meter (12 x 42 inches), the moldline contour radius 12.2 meters (480 inches) as well as the location and size of the 12 moldline slots and the hat section stiffeners.

6.4.3 TOOL DESIGN AND TOOL FABRICATION

Tooling drawings were prepared after completion of the engineering drawing. Two types of tooling drawings are required: (1) an assembly drawing which shows the detail stacking, sizes, and replacement of the detail parts which are used in the SPF/DB assembly; and (2) a forming tool drawing which shows the detail dimensions for both the male and female dies to be used for the SPF/DB operation.

The forming tool, because of its size, required compensation for thermal growth. This meant that the centerlines of each individual hat section had to be adjusted a predictable distance from the centerline of the tool.

The forming tool drawing was submitted to local machine shops for bid and the lowest bidder (L. F. Purkey Company) was awarded the contract. After completion by the vendor, Rockwell technicians added indexing pins and detail part locating pins and welded the gas management manifold to the tool. Each individual hat section had to be vented to assure adequate purging during heat-up and while the bonding took place. This required the drilling of 24 holes and manifolding of each. Figure 55 shows the completed tool.

6.4.4 DETAIL PART FABRICATION

Detail parts, as shown in figure 56, were machined to conform to the tooling assembly drawing. Mylar overlay sheets were prepared with reference lines for each hat section, and corrected for thermal growth. These were used to locate the plenum vent holes and to locate the individual details during layup. These parts, with the exception of the hat section cap doublers, were then assembled into a "pack." Figure 57 shows the pack partially assembled. This assembly consisted of the detail machined parts, together with the large titanium sheets with stop-off compound applied, as required. In addition to the cap reinforcement, each hat section stiffener requires two detail parts. For the second and subsequent panels, these two sets of 12 detail parts were combined into two sheets, eliminating a considerable amount of machining time, as well as simplifying the assembly of the "pack." The extra material was later removed during chem-mill operations.

6.4.5 SPF/DB CYCLE

The SPF/DB process was performed in a 4500 ton hydraulic press with ceramic heating platens surrounding the forming tools. (Figure 58). Because of the thermal mismatch between the tool (22-4-9 CRES) and the titanium 6Al-4V work-piece, the part had to be unloaded hot, otherwise the part would "lock" into the tool. Figures 59 and 60 show typical panels after removal from the die.

Gas management was an anticipated problem and did present complications. The tool was designed with relief grooves to provide a gas path between the 12 hat sections. There were no relief grooves at the inlet and outlet ends. Gas injection tubes were expected to inflate the first section and exhaust through the twelfth section. On the first trial, excessive flow forming of the pack into the relief grooves, blocked the gas flow between sections. The inlet and outlet tubes were pinched and the gas path was cut off.

On the third and subsequent runs, the relief grooves between sections, were widened and end relief for the inlet and outlet tubes was added. This allowed adequate flow of gas, resulting in uniform and equal inflation of all twelve hat sections.

Outer moldline smoothness was anticipated to be a possible problem above each plenum. Therefore, a steel diaphragm was bonded to the upper face sheet on all panels except 5 to stiffen it and reduce the probability of forming grooves on the surface. While this did prevent plenum related grooving, the fourth demonstration panel did have minor depressions at the first and twelfth sections of .89 mm (.035 inch) deep by 22 mm (.89 inch) wide. The second and eleventh sections were about .686 mm (.027 inch) deep by 22 mm (.89 inch), and the undulating surface decreased at the third and tenth and was almost nonexistent at the fourth and ninth section. The remaining sections showed no distortion.

The cause of this distortion is not fully understood. One theory is trapped gas between the steel diaphragm and the upper tool, and the other is "oil canning" resulting from thermally induced stresses caused by the thermal mismatch between the part and the tool which generated before the part could be removed. The surface was flattened by a second run, inflated to 2,068,000 N/M² (300 psi) for two hours at 843° C (1550° F).

Five development panels were fabricated before producing the final feasibility panel. After each trial, corrections, as described above, were made to the tooling or pressure/temperature cycle until all anomalies had been eliminated. The sixth panel was fabricated as the final feasibility demonstration panel. The development sequence of the panels is shown below.

Panel No.	Run No.	Effective Strain Rate cm/cm/sec (in/in/sec)	Results	Corrective Action
1	1	3×10^{-4}	Initial bonding accomplished. Forming pressure did not reach interior of "pack."	Tool relief should be machined in area of stop-off strips.
2	2	3×10^{-4}	Initial bonding accomplished. Forming pressure did not reach interior of "pack."	Interior plumbing should be revised. Press pressure should be reduced. Gas passages in panel must be reopened.
2	3	3×10^{-4}	Initial bonding accomplished. First hat formed, but others ruptured before complete forming.	Strain-rate should be reduced.
2	4	2×10^{-4}	Initial bonding accomplished. Panel ruptured before complete forming.	Strain-rate should be reduced. Change die lubricant.
4	5	1×10^{-4}	Panel formed and bonded as planned except for minor moldline deviation.	Increase time of forming pressure with panel replaced in die.
4	6	1×10^{-4}	After hot sizing for 2 hours $2,068,000 \text{ N/M}^2$ (300 psi) at 843° C (1550° F) moldline deviations reduced to .016 maximum. Selective chem-milling used to eliminate moldline deviation. During final chem-milling more moldline deviations appeared. Internal plenums were progressively smaller in size, producing unacceptable plenums.	Larger locating pins should be used to assure correct position of plenums. Press should be held open to prevent damping at one end during heatup. Steel plate should be eliminated to prevent differential cooling.

Panel No.	Run No.	Effective Strain Rate cm/cm/sec (in/in/sec)	Results	Corrective Action
5	7	1×10^{-4}	Panel formed and bonded as planned. Plenums did not form.	Silk screen pattern must be indexed properly. Steel plate should be used on moldline surface.
6	8	1×10^{-4}	Panel formed and bonded as planned. Moldline surface met smoothness requirement. Plenums formed satisfactorily, as shown in figure 61. Panel moldline contour did not meet 12.2 m (40 ft.) radius specified.	Panel stress-relieved in female die to restore proper radius.

6.4.6 CHEM-MILL

Chem-milling is used for two purposes on SPF/DB panels:

1. Removal of surface contamination. - SPF/DB parts are removed from the tooling at temperatures no lower than 760° C (1400° F). Titanium surfaces that are exposed to the atmosphere at this temperature are readily contaminated. Chem-milling a minimum of .13 mm (.005 inch) from all surfaces removes the contamination.
2. Removal of parent material for sizing to the final dimensions. After the SPF/DB part is removed from the tooling, chem-milling is used to remove excess material that was needed to control the bonding and forming process. Selective, multi-stage chem-milling was also used to eliminate minor contour deviations.

6.4.7 SLOTTING

As described previously, the slotting methods investigated during the fabrication of the demonstration panels (Section 4.3) were laser machining, electron beam cutting, electrical discharge machining (EDM), using a wire anode or a sheet anode, and mechanical sawing. Of these, the sheet anode EDM and the mechanical sawing system produced the best results. Competitive bids for the two systems on the feasibility panel showed that the EDM method would cost 29 percent less than the other. This, coupled with the superior slot quality, produced in Task II, led to the selection of EDM for the panel. Figure 62 shows the panel which has been slotted by this method.

6.4.8 QUALITY CONTROL

To meet the contract requirements, two quality control procedures were imposed on the panel; dimensional inspection and radiographic inspection. The dimensional check assures that the part meets the design requirements of Section 4.1 Criteria, and of the panel drawing, figure 54. The radiographic (X-ray) inspection verifies the diffusion bond between the adjacent titanium surfaces.

Dimensional inspection by Rockwell inspectors showed all critical dimensions to be within specified tolerances.

X-ray inspection revealed that on panel number 6, the plenums formed as specified on the drawing. X-ray photographs of earlier panels with improperly joined plenums were used as a guide to interpret the photos of the good panel.

6.4.9 FINAL FEASIBILITY PANEL

Figures 63 and 64 show panel number 6. It is the final panel produced and has been delivered to NASA.

7.0 DISCUSSION OF RESULTS

The accomplishments of this program have (1) revealed several new possibilities for LFC wing designs; (2) established new parameters for fabrication of SPF/DB panels.

7.1 DESIGN CONCEPTS

On the basis of minimum weight, ease of inspection, joint simplicity, and tailorability to varying load levels, the hat-section, semisandwich concept used for the feasibility panel represents the best design for LFC wings.

Of the types of sandwich structure investigated, the sinewave truss core is recommended because of its lower fabrication costs.

The SPF/DB designs offer high structural efficiency, with the hat-stiffened feasibility panel operating at an average compressive stress of 94 percent of ultimate. The SPF/DB titanium designs investigated are not fatigue-critical, thus allowing them to operate at maximum structural efficiency.

7.2 FABRICATION CONSIDERATIONS

Thermal mismatch between the steel tool and the titanium part must be compensated for during the tool design.

To prevent lockup in the tool, SPF/DB parts, such as the hat-stiffened panels, must be removed while they are still hot. For large parts, a hot ejection system would be required.

Two methods are available for forming the internal plenum:

1. Steel inserts which are removed after the SPF/DB cycle.
2. Use of the forming cycle to produce the plenum.

The SPF/DB process can produce moldline contours within required tolerances. The use of a separate sacrificial steel plate on the moldline surface during the SPF/DB cycle results in the best contour control, but can introduce residual stresses in the panel unless it is removed immediately after forming, and before the panel cools.

Where moldline deviations do occur in the detail forming process, they can be removed by any one of several current salvage procedures. These include hot sizing in the forming tool or selective chem-milling during the final chem-mill operation.

7.3 RECOMMENDATIONS FOR FUTURE WORK

The lessons learned during this program have indicated that the application of SPF/DB to laminar flow wings opens a whole new field of structural concepts. Although feasibility of some of the concepts has been demonstrated in this program, much additional work will be required before this approach can be applied to a full scale commercial transport. The following recommendations are presented as the next step in the development of SPF/DB for LFC wing structure.

These examples point out the advantages of a replaceable outer skin which will allow the basic structural panel to be salvaged if the outer surface is damaged. Methods of fabricating an LFC wing with a replaceable moldline surface and its related plenums and methods of attaching it to the substructure should be investigated.

7.3.1 Surface Repairability

One of the problems in fabricating demonstration panels was encountered in machining the moldline slots. Cutter breakage or EDM electrode misalignment produced local variations in slot width, which on a production panel would require repair. Similar problems occurred in the perforating of panels employing holes instead of slots. Improper setting of the electron beam drilling machine resulted in holes which did not fully penetrate the surface.

7.3.2 Full Scale Wing Design

This program has addressed the details of an LFC wing design only in the center of the panel for one specific load level. To fully assess the potential of the SPF/DB structure, significant features of an entire wing would be developed, including the following:

- ° Various Load Levels. Mechanically joined structural elements tend to become inefficient at lower load levels because of overlapping material required to provide edge distance for fasteners. The more efficient joining achieved in SPF/DB structure, as compared to conventional structure, will usually become increasingly more efficient in the vicinity of the wing tip, where load levels are reduced.

- ° Joints and Splices. For a transport aircraft, the wings are usually constructed of several spanwise planks to provide protection against fatigue failures. Methods of joining these planks using SPF/DB concepts should be developed. Also, studies of methods for fabricating these spanwise planks in one piece using SPF/DB are required, or methods of producing fatigue resistance, chord-wise joints should also be developed for comparison with the continuous plank design.
- ° Internal Ducting. This program has demonstrated the feasibility of the SPF/DB panel with provisions for ducting boundary layer air into the interior of the panel. However, methods of ducting this air from the panels to collection ducts which transfer the air from the panels to the pumps have not been investigated. This interface and the methods of joining the collection ducts should be addressed in the complete wing design.

7.3.3 Cost Comparisons

In addition to offering new approaches to LFC wing design, unobtainable by other methods of construction, SPF/DB structure may be lower in cost and weight than conventional structure. Previous studies on non-LFC wing (reference 7) have shown SPF/DB titanium to be lower in both cost and weight than conventional aluminum and competitive with advanced composites. Total systems costs should be determined to establish actual direct operating costs (DOC's) for cost trades.

7.3.4 Demonstration Hardware

The next steps in hardware fabrication are the scale up to large SPF/DB structures and the fabrication of some of the critical wing features. Wing panels approximately one by three meters (40 x 120 inches) would be the next logical size to demonstrate. This would provide a panel of the maximum chordwise dimension for a typical wing plank.

Fabrication of typical panel splices and joints using SPF/DB panels should be accomplished to confirm the producibility of the concept.

Methods of producing internal ducting, compatible with the SPF/DB panels should be demonstrated as a preliminary step in the suction system development.

7.3.5 Fatigue Testing

Tests on SPF/DB panels for non-LFC wings have indicated that their fatigue properties exceed those of conventional structure. However, some

features of the LFC wing panels, such as the internal metering holes, would tend to reduce the fatigue life. Even though preliminary analysis has shown that the SPF/DB panels are still not critical in fatigue, this should be verified by test to gain full acceptance for the concept.

8.0 CONCLUSIONS

This study of the application of SPF/DB titanium structure to LFC wing structures has produced three 15 x 23 cm (6 x 9 inch) demonstration panels and one .30 x 1.0 m (12 x 42 inch) feasibility panel from which the following conclusions can be drawn.

- ° The SPF/DB process is capable of producing hardware to the mold-line tolerances specified in paragraph 5.2 for laminar flow control surfaces.
- ° The SPF/DB process is capable of producing an LFC panel incorporating integral plenum chambers and ducting, with either slots or perforations in the moldline.
- ° Both integrally stiffened skin panels (typical of multi-rib wings) and sandwich panels (typical of multi-spar wings) can be produced by the process as demonstrated by the fabrication of the 13 x 23 cm (6 x 9 inch) panel.
- ° The walls of the plenums and internal air passages can be used as structural elements, servicing as primary load carry material, thus avoiding the use of parasitic LFC material.
- ° Slots in a moldline surface for boundary layer suction can be produced in a variety of ways. However, electrical discharge machining with a copper sheet anode produces the cleanest slots and at lowest cost of the five methods investigated.
- ° Scale-up from subscale to full-scale SPF/DB panels introduces new problems which will require additional development programs.

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9.0 REFERENCES

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4. Sturgeon, R. F., Bennett, J. A., Etchberger, F. R., Ferrill, R. S., Meade, L. E.: Study of the Application of Advanced Technologies to Laminar-Flow Control Systems for Subsonic Transports. NASA CR-133949, May 1976.
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7. Clemens, J. D., Gardner, W. J., and McQuilkin, F. T.: Air-to-Surface Fighter Structural Studies. TFD-77-1124, Los Angeles Division of Rockwell International Corporation, November 1977.

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APPENDIX A

SUPERPLASTIC FORMING WITH CONCURRENT DIFFUSION BONDING (SPF/DB)

Titanium and some of its alloys exhibit unique characteristics at elevated temperatures which have permitted the development of the advanced technology of concurrent superplastic forming and diffusion bonding (SPF/DB). The optimum temperature for superplastically forming Ti-6Al-4V is 927°C (1700°F). Fortunately, it is the same temperature used to diffusion bond titanium structures. Therefore, the SPF/DB processing of structure is accomplished during a single heat cycle.

In the SPF/DB process, mating surfaces are brought into intimate contact at elevated temperature. Atomic diffusion across the interface produces the bond. Test specimen bonds fabricated by using gas pressures in the SPF/DB process exhibit parent metal strength. Lap shear strengths, for example, averaged $5.8 \times 10^8 \text{ N/m}^2$ (84,000 psi). Typical 6Al-4V shear strength is $5.4 \times 10^8 \text{ N/m}^2$ (78,000 psi).

Independent research at Rockwell has now established three generic types of SPF/DB structures (figure A-1). In the first type, a superplastically forming sheet encounters titanium details, preplaced in the tooling, and is concurrently diffusion bonded to them. It is, therefore, possible to add functional members to the formed part (figure A-2). The procedure can also incorporate forming after bonding because both are done during a single-process (heating) cycle.

The second type of SPF/DB structure - integrally stiffened - is made by simultaneous processing of two 6Al-4V sheets (figure A-1B). A stopoff compound applied to one sheet prevents bonding in discrete areas. The stopoff pattern corresponds to tooling cavities. When the pack reaches 927°C (1700°F), pressure is applied and those areas not coated with stopoff are bonded. After bonding, gas pressure is introduced which superplastically forms the unbonded areas. Some of the variations possible are shown in figure A-5.

By using selective bonding and three sheets, the SPF/DB process yields the most advanced form of hardware--expanded sandwich (figure A-1C). A variety of demonstration SPF/DB sandwich structures have been fabricated. Although the work is still in an early stage, two important advantages of SPF/DB sandwich can be cited:

1. The external configuration of the fabricated part is obviously determined by the tool cavity and may be a design variable. On the other hand, the core configuration is determined by the

stopoff pattern; it may be of infinite variety and can be modified without tooling change.

2. The process inherently provides an integral edge closure. This avoids what is frequently a significant cost factor in applying conventional honeycomb sandwich. Figure A-4 shows typical representative core configurations that have been fabricated to date, including a truss core, dimpled core (core bonded to face sheets in intermittent spot pattern), and sine wave core (core bonded in a parallel sine wave pattern). The process also readily permits core variations within the same panel; i.e., all types of core can be utilized within the same panel by varying the stopoff pattern if an advantage can be gained with this approach.

TABLE 1

WING STATIC LOADS

STA(%)	BP		MOMENT-LIMIT		N _x -ULT.		V-LIMIT	
	in.	m	in-lb x 10 ⁶	MM-m	lbs/in.	kN/m	lbs x 10 ³	kN
.95	1065	27.05	.17	.019	* -809	* -142	7.0	31.14
.75	841	21.36	4.8	.54	-11,000	-1,927	35.0	155.68
.55	617	15.67	17	1.92	-24,000	-4,205	70.0	311.36
.37	414	10.52	39	4.41	-36,100	-6,325	120.0	533.76
.14	157	3.99	77	8.70	-24,200	-4,240	200.0	889.6
.08	ROOT							
*Negative "N _x " denotes compression load in upper wing surface.								

For durability requirements, the following criteria have been selected:

Service Life	50,000 hours
Average flight duration	2 hours
Limit load factor	3g
Typical flight spectrum	20 cycles 1g $\pm$ 1/5 g
	+40 cycles 1g $\pm$ 1/10 g
Ground-air-ground cycles	25,000
Scatter factor	2

SUMMARY

		WITHOUT CAP			WITH CAP		
PITCH		88.90 mm (3.5 in)	177.80 mm (7 in)	88.90 mm (3.5 in)	177.80 mm (7 in)		
GAGES	TYPE OF SEMISANDWICH	SEMI - CIRCLE	TRAPE - ZOIDAL	SEMI - CIRCLE	TRAPE - ZOIDAL	SEMI - CIRCLE	TRAPE - ZOIDAL
	E	8.0086 mm (.3153 in)	7.4879 mm (.2948 in)	6.248 mm (.246 in)	6.096 mm (.240 in)	7.186 mm (.2829 in)	6.020 mm (.237 in)
	t _F	2.413 mm (.095 in)	1.778 mm (.07 in)	3.556 mm (.14 in)	3.683 mm (.145 in)	2.794 mm (.11 in)	1.905 mm (.075 in)
	t _C	6.248 mm (.246 in)	5.283 mm (.208 in)	3.302 mm (.13 in)	2.609 mm (.1027 in)	.457 mm (.018 in)	1.600 mm (.063 in)
	t _C	9.804 mm (.386 in)	11.430 mm (.45 in)	5.182 mm (.204 in)	4.826 mm (.19 in)	.719 mm (.0283 in)	3.810 mm (.15 in)
	t _{CAP}	0	0	0	0	11.938 mm (.47 in)	9.144 mm (.36 in)
WEIGHT COMPARISON %		38	29	7	5	24	3
WEIGHT RANK		8	7	5	3	6	2
						BASE LINE	
						1	4

NOTE: THE GAGES ARE STRESS ANALYSIS RESULTS ONLY. DESIGN AND PRODUCTION CRITERIA MUST BE CONSIDERED.

TABLE 2

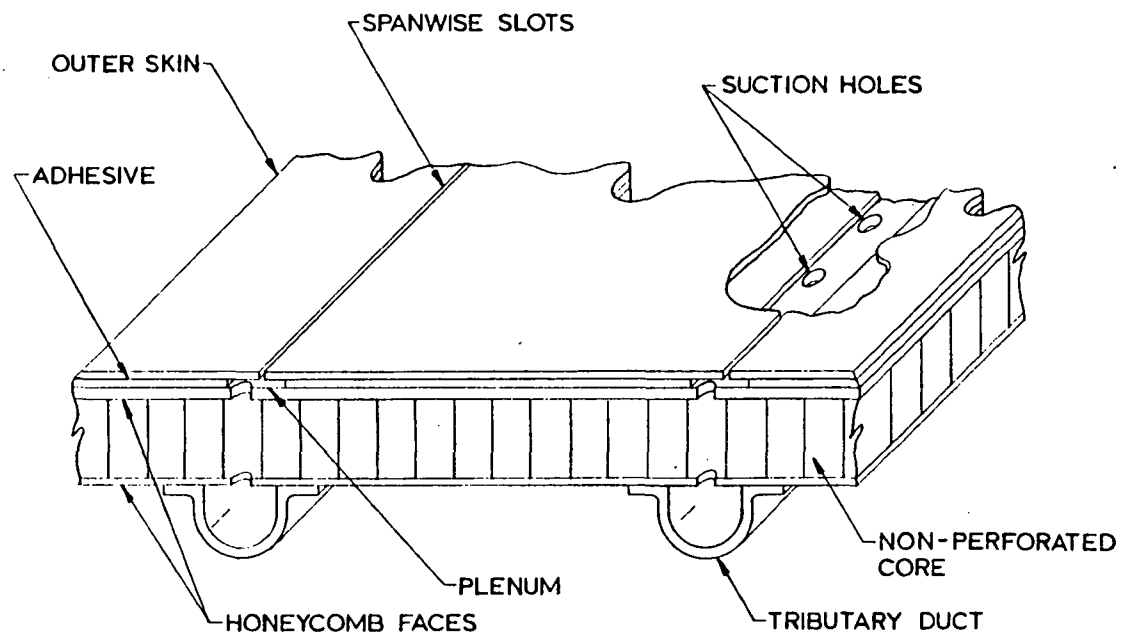
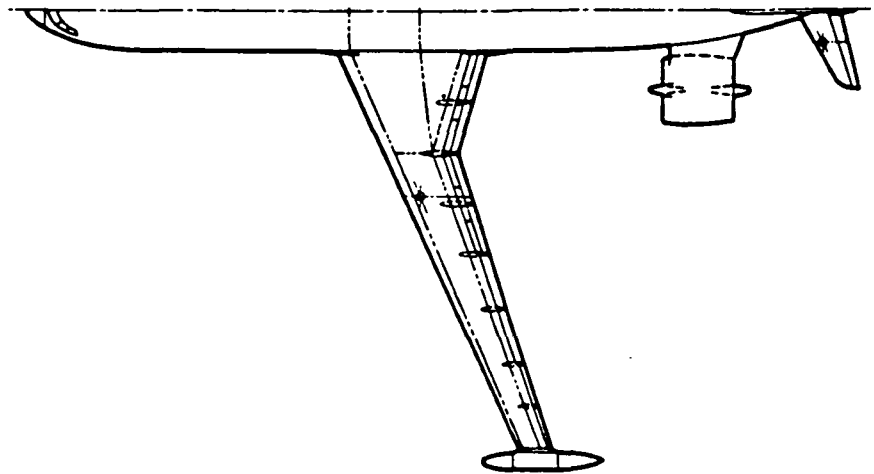


Figure 1

TYPICAL OUTER SKIN PANEL CONSTRUCTION



Cruise Speed, $M = 0.80$
 Cruise Altitude, $m(ft) = 11,582(38,000)$
 Wing Sweep, $rad(deg) = 0.396(22.7)$
 Aspect Ratio, $= 14.00$
 Wing Area, $m^2(ft^2) = 231.7(2494)$

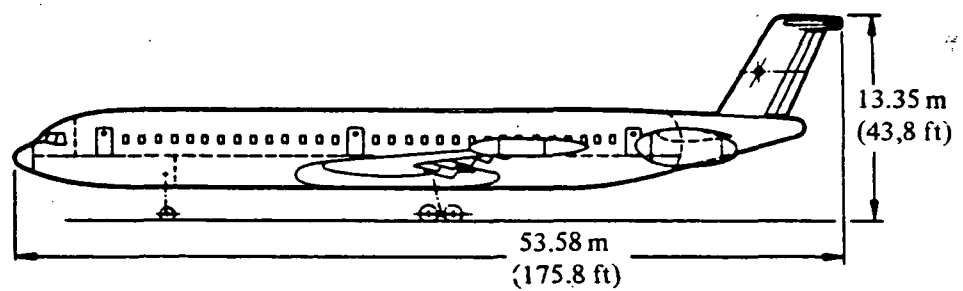
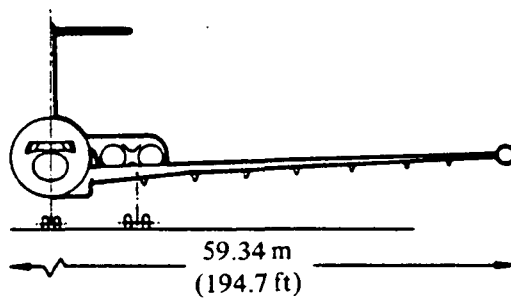
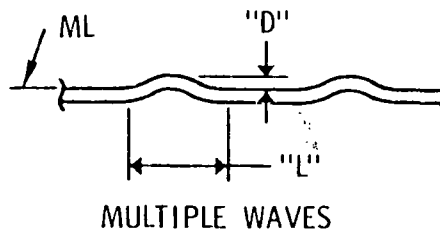
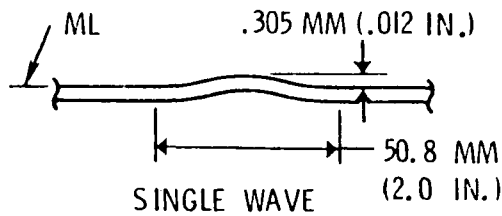
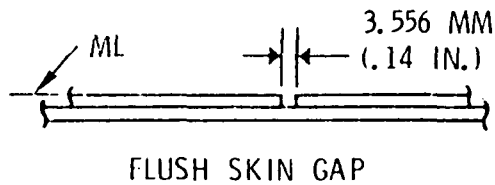
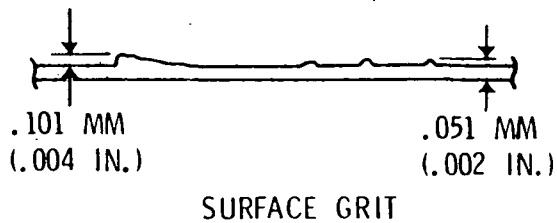
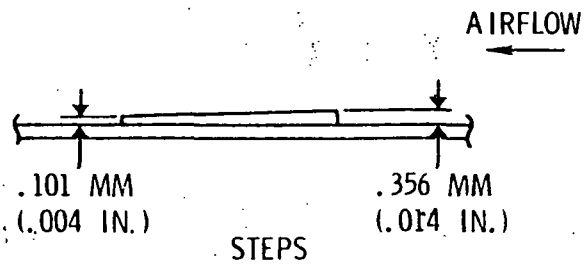


Figure 2 General arrangement, LFC-200-R



"D"	"L"
.076 MM (.003 IN.)	12.7 MM (.5 IN.)
.152 MM (.006 IN.)	50.8 MM (2.0 IN.)
.305 MM (.012 IN.)	203.2 MM (8.0 IN.)

Figure 3 Surface Smoothness Criteria

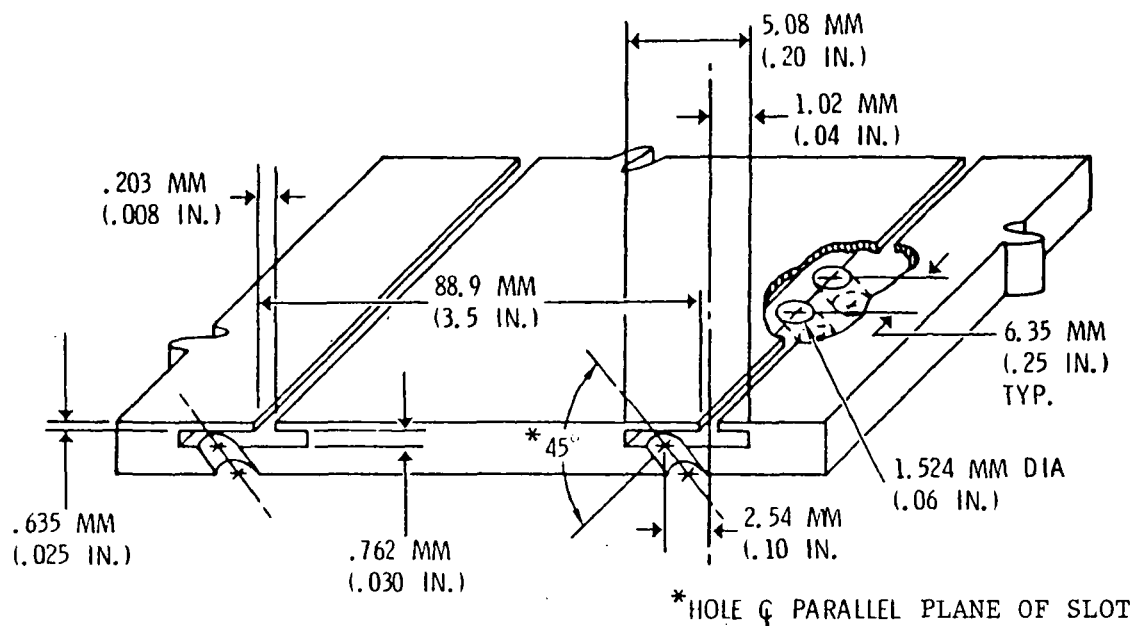


Figure 4 Slotted Wing - Upper Surface

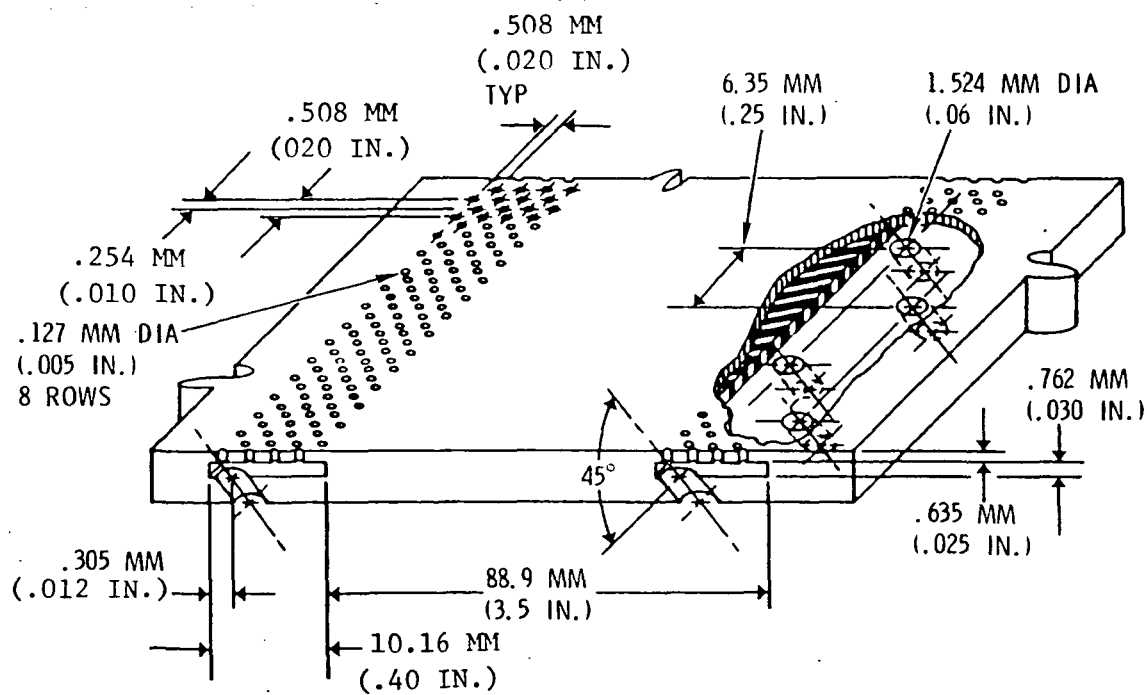
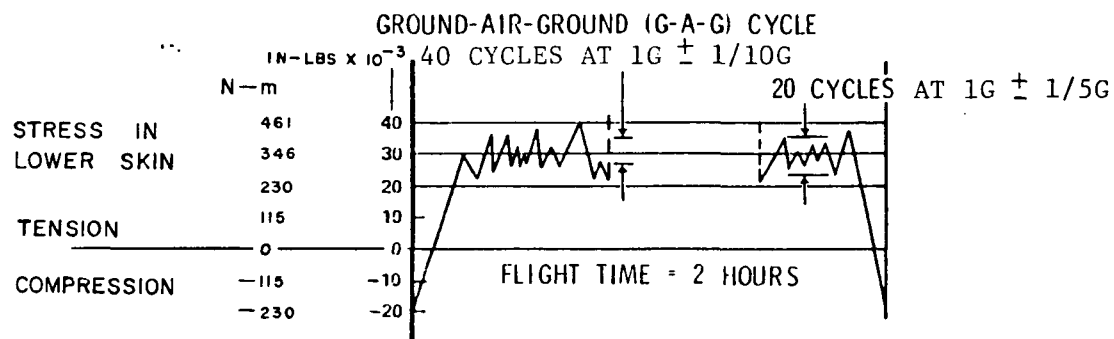


Figure 5 Perforated Wing - Upper Surface



- 50,000 HOUR LIFE
- 2 HOURS/ FLIGHT
- SCATTER FACTOR = 2

TOTAL FATIGUE REQ'MT

25,000 G-A-G CYCLES X 2 = 50,000

1,500,000 GUST/MANEUVER CYCLES X 2 = 3,000,000 CYCLES

Figure 6 Fatigue Criteria

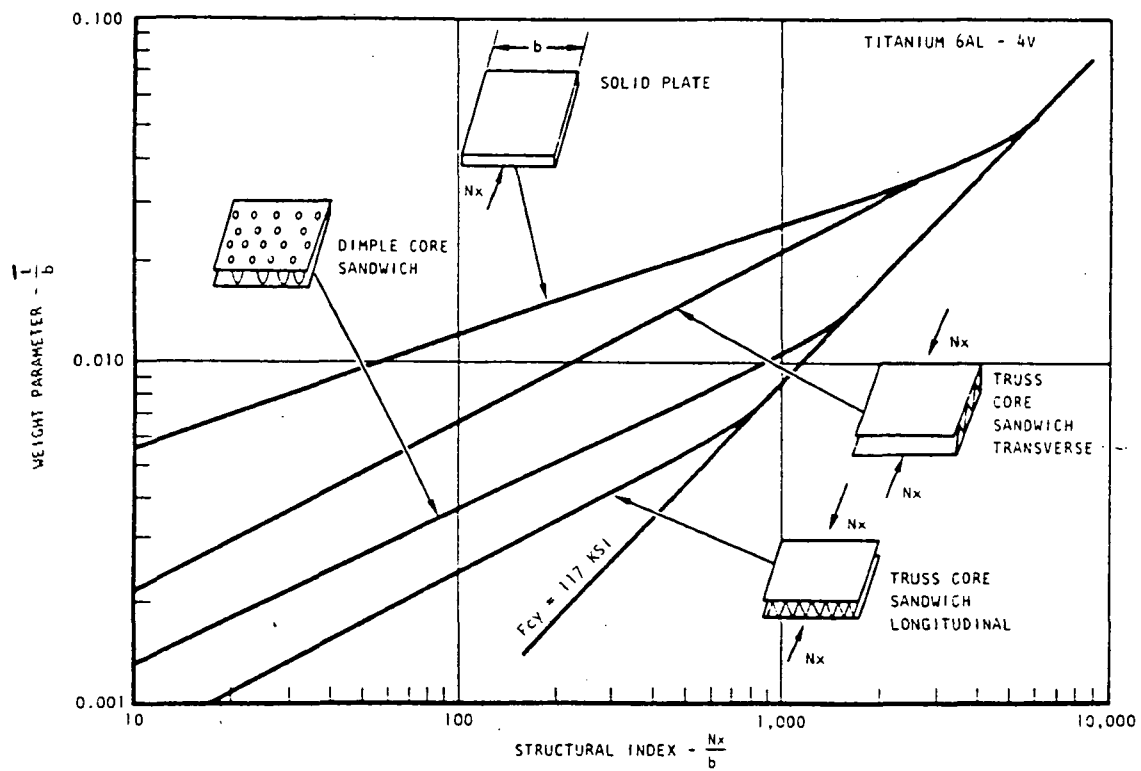


Figure 7 Compression Panels, Titanium 6AL-4V Annealed

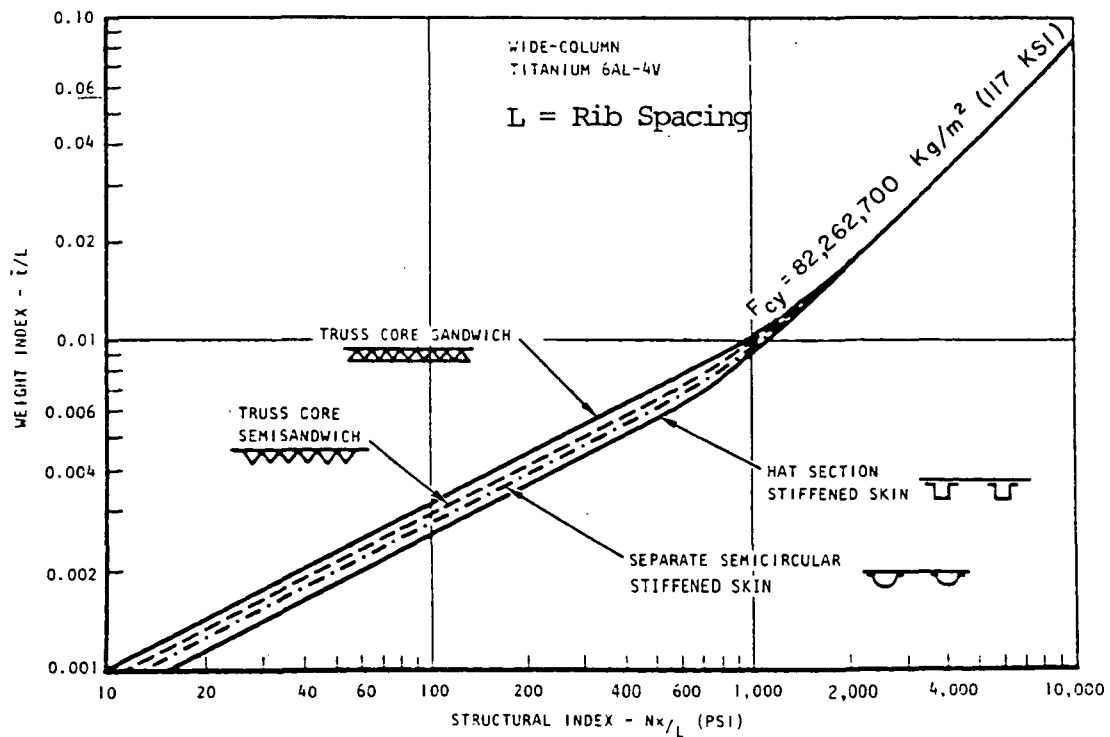
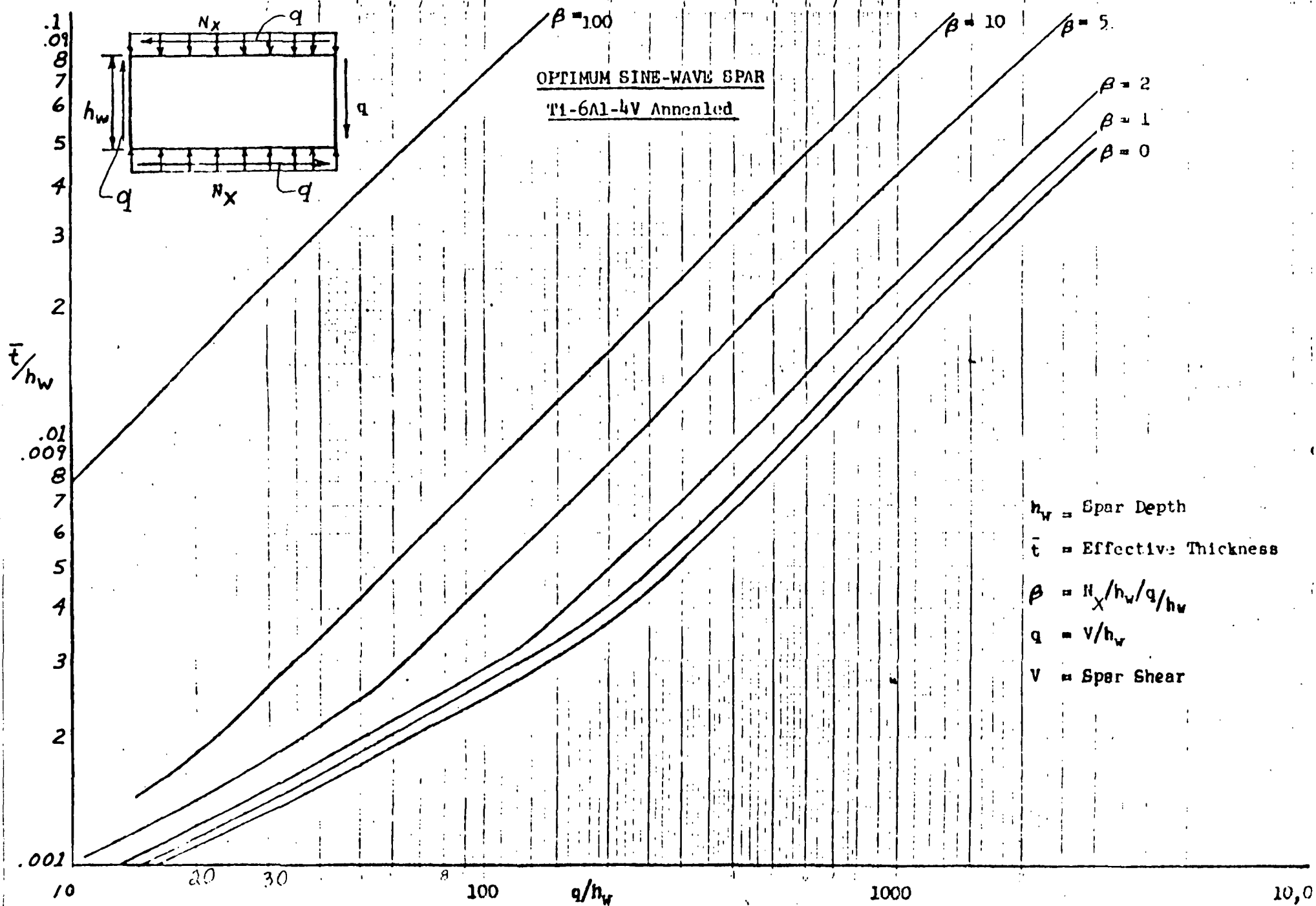
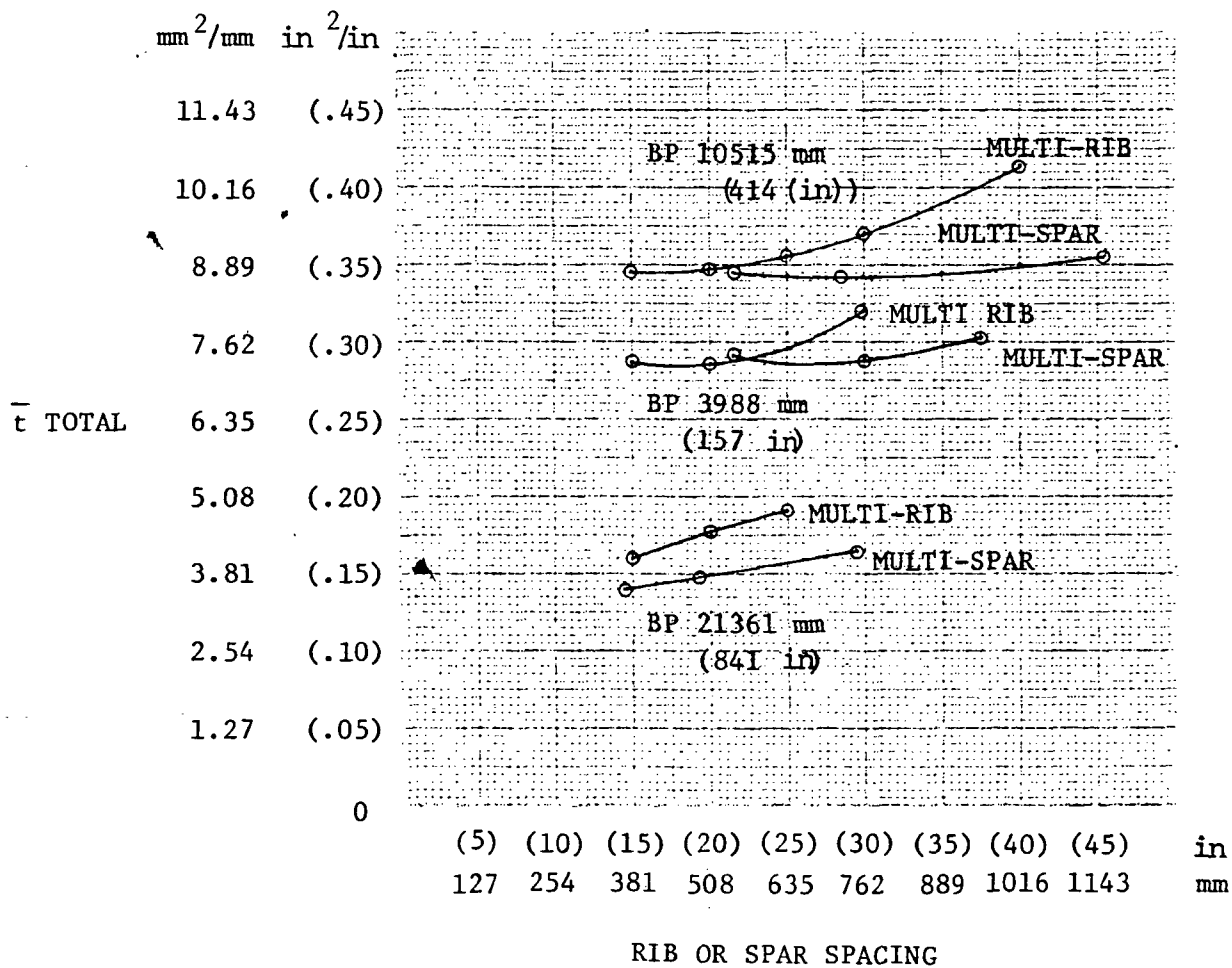


Figure 8 Wide Column Configurations, Titanium 6AL-4V Annealed





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Figure 10

Wing Design, LFC-200-R
(Multi-Rib vs. Multi-Spar)

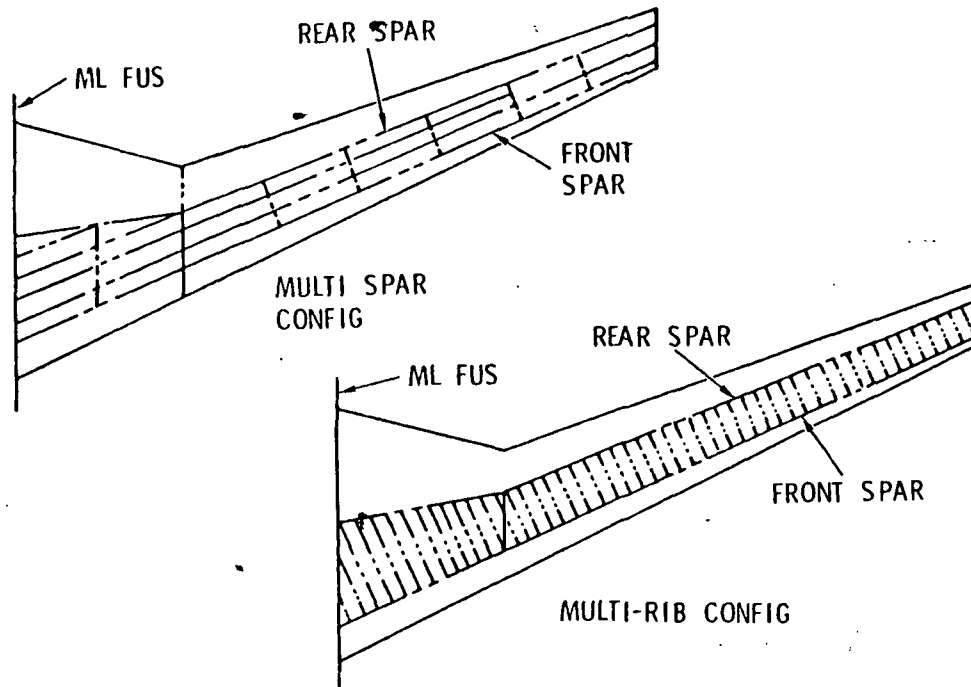


Figure 11

Wing Design LFC-200-R
Multi-Rib & Spar Configuration

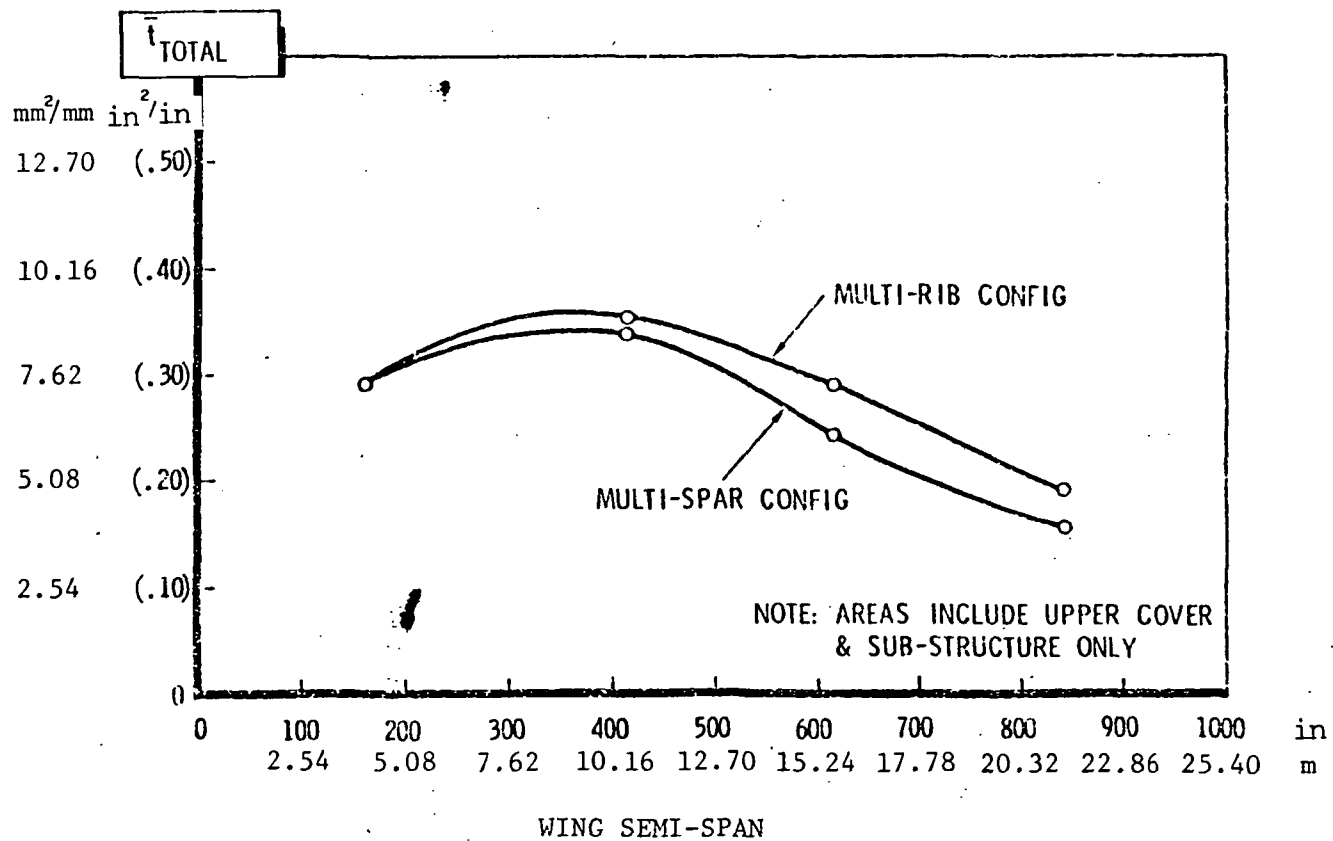


Figure 12

Wing Structural Requirements

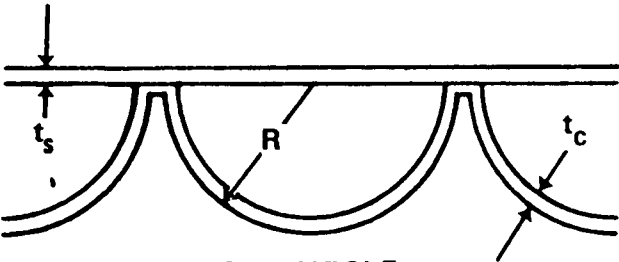
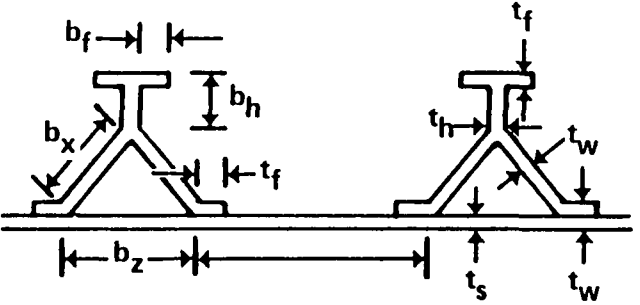
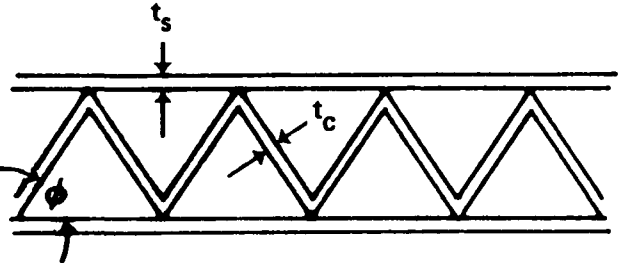
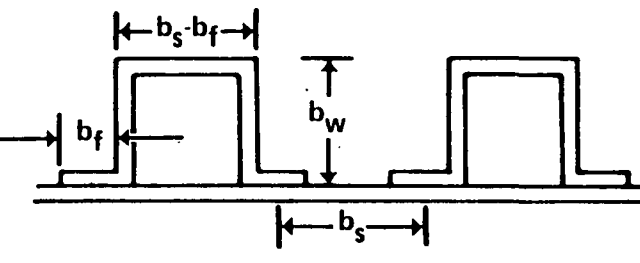
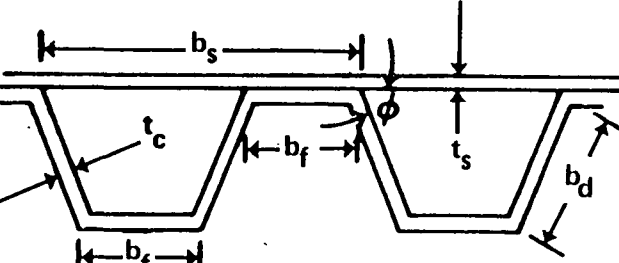
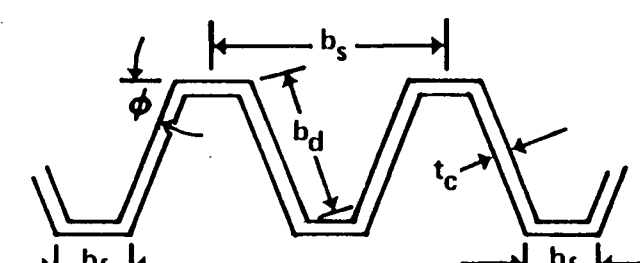
 SEMICIRCLE CORRUGATION SEMI-SANDWICH	$\epsilon_{MAX} = .706$ $t_c/t_s = 0.23$	 STRAIGHT Y-TEE STIFFENED	$\epsilon_{MAX} = 1.23$ $b_w/b_s = 0.90$ $t_w/t_s = 0.90$
 TRUSS CORE SANDWICH	$\epsilon_{MAX} = .605$ $t_c/t_s = 0.92$ $\phi = 62^\circ$	 HAT SECTION STIFFENED	$\epsilon_{MAX} = .928$ $b_w/b_s = 1.0$ $b_f/b_w = 0.3$
 TRAPEZOIDAL CORRUGATION SEMI-SANDWICH	$\epsilon_{MAX} = .685$ $b_f/b_d = 0.18$ $\phi = 70^\circ$	 TRAPEZOIDAL CORRUGATION	$\epsilon_{MAX} = 1.60$ $b_f/b_d = 0.85$ $\phi = 60^\circ$

Figure 13

Panel Structural Optimization
(Wide Column Concepts)

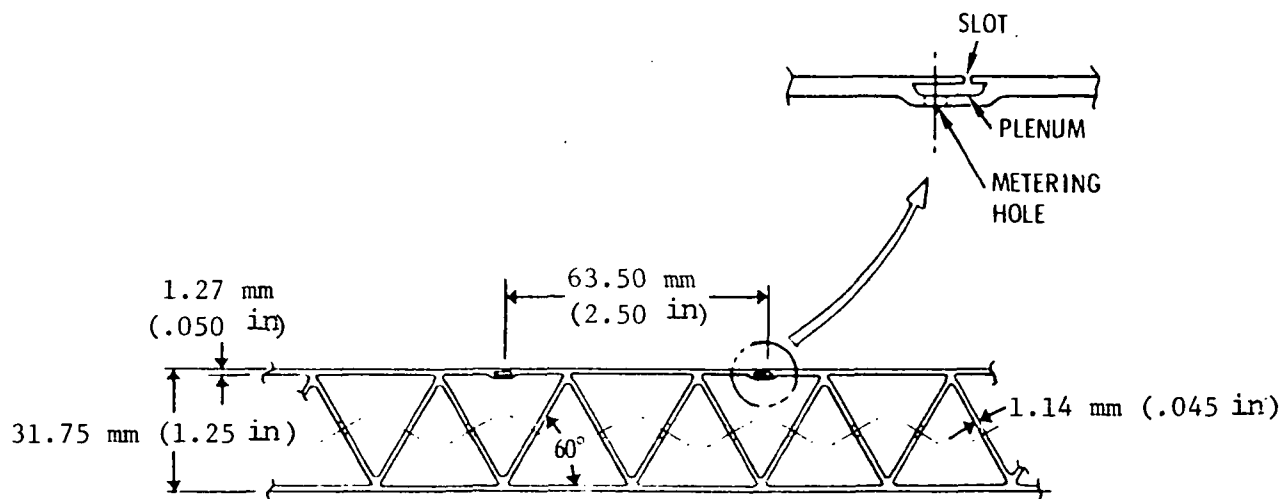


Figure 14

Concept A

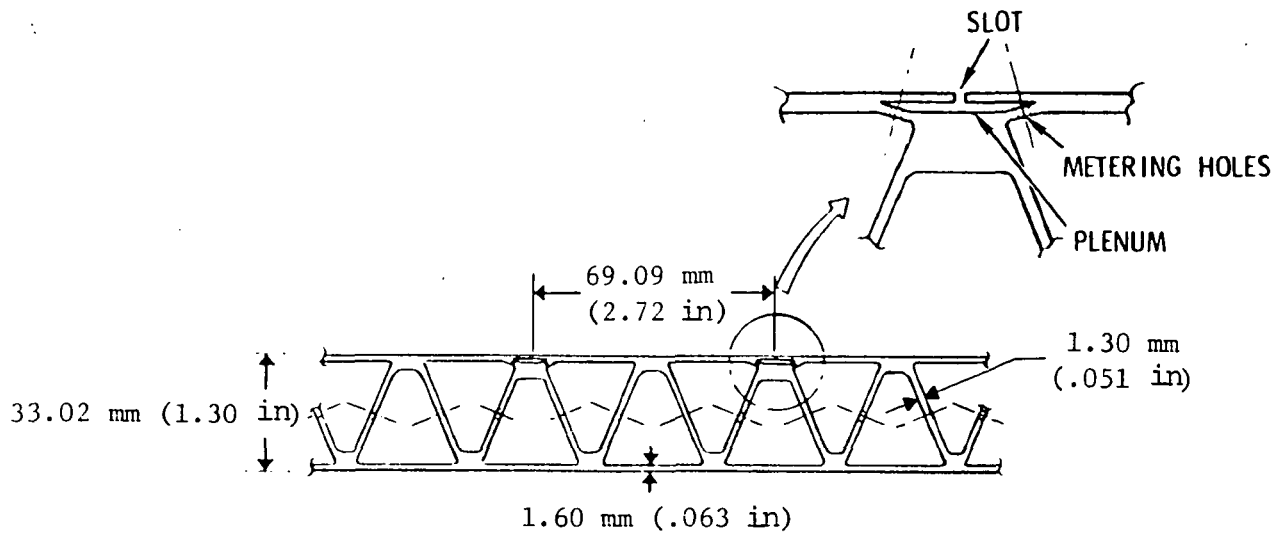


Figure 15 Concept B

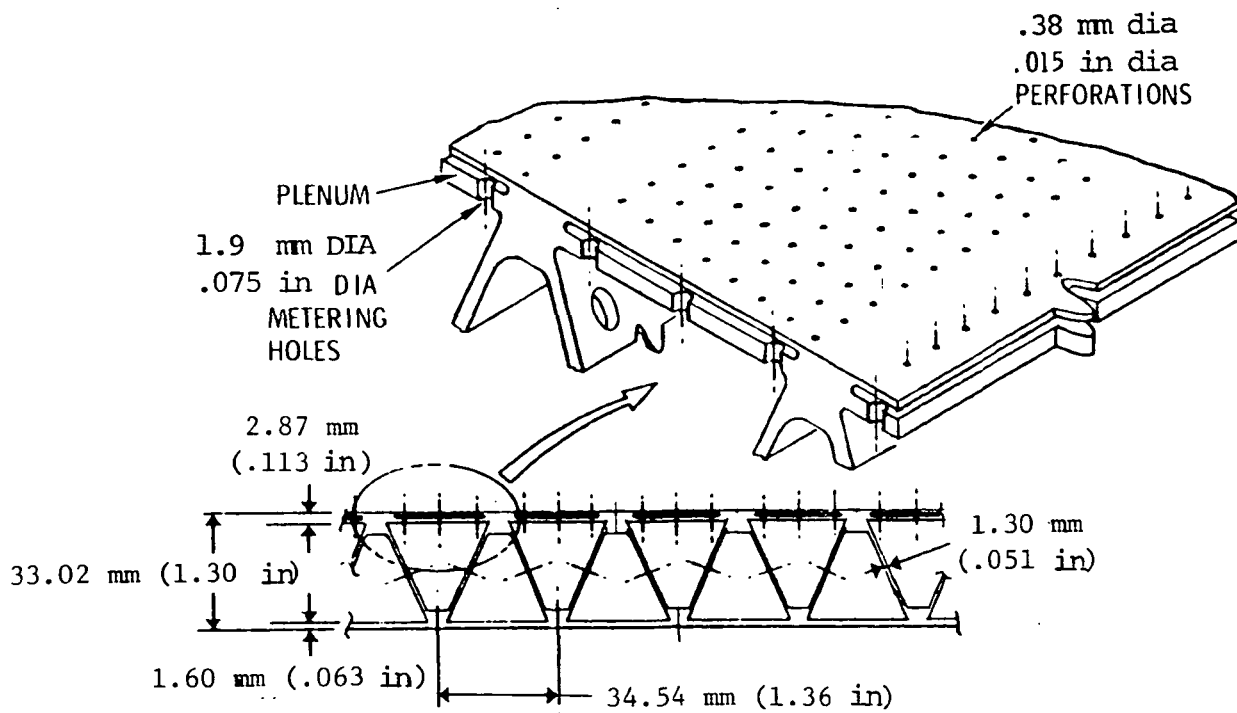


Figure 16 Concept C

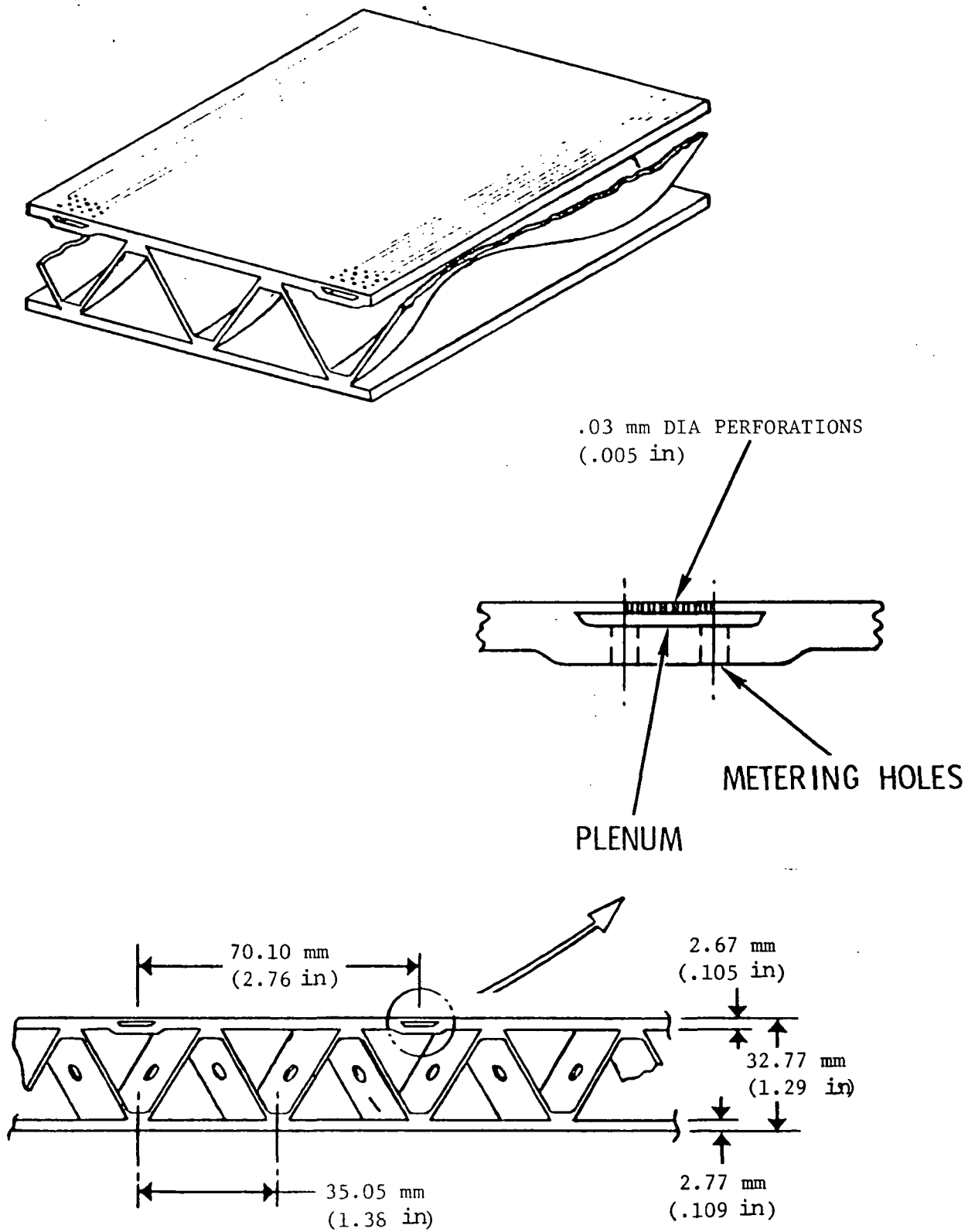


Figure 17

Concept D

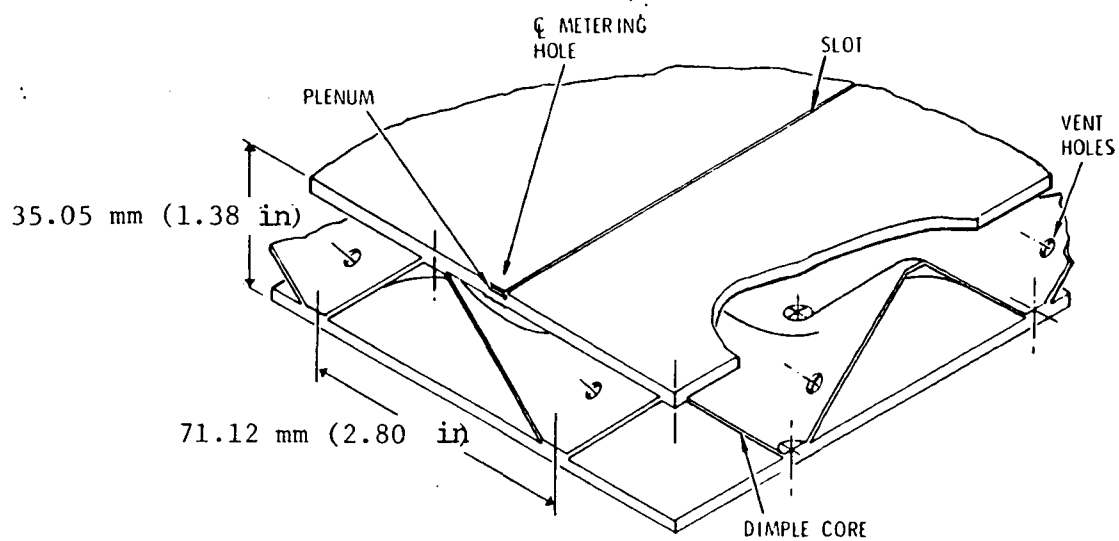


Figure 18 Concept E

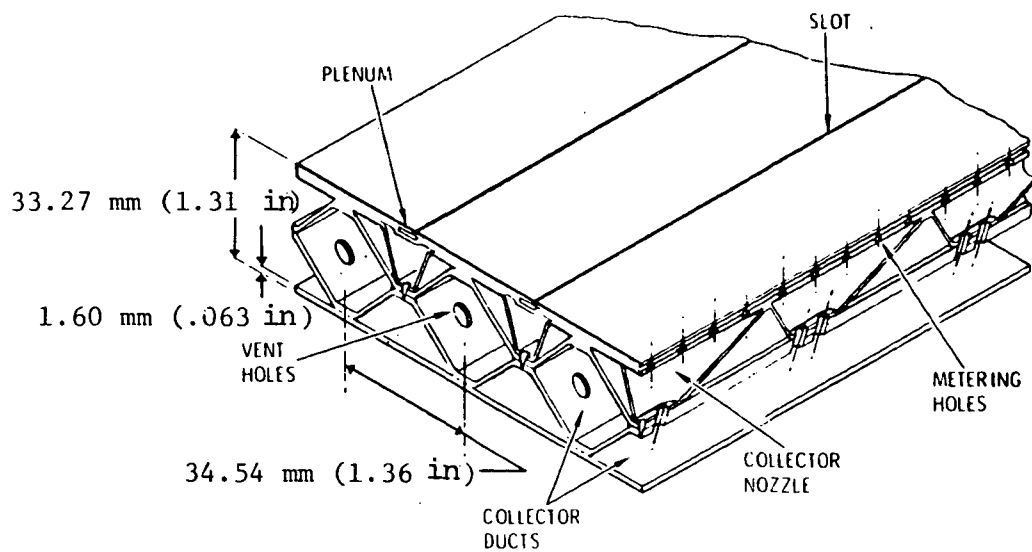


Figure 19 Concept F

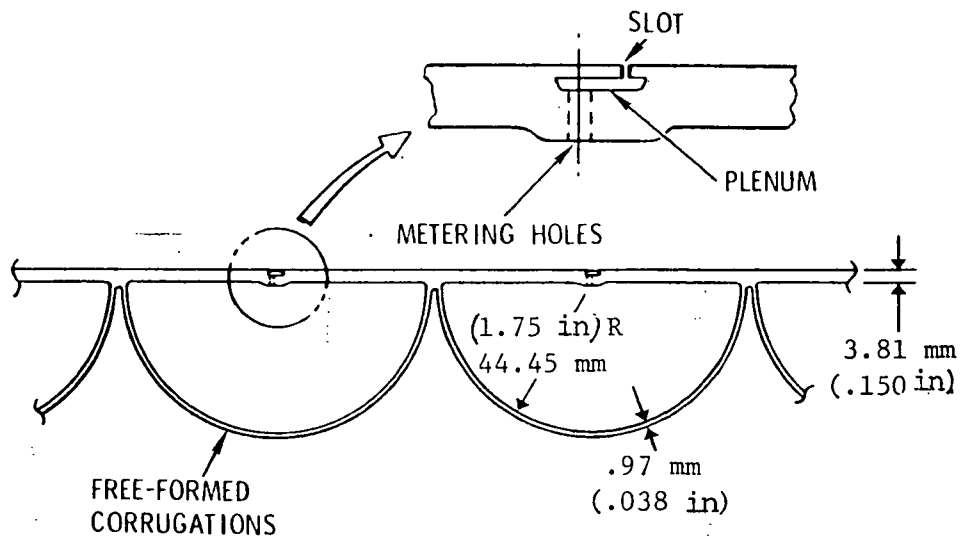


Figure 20

Concept G

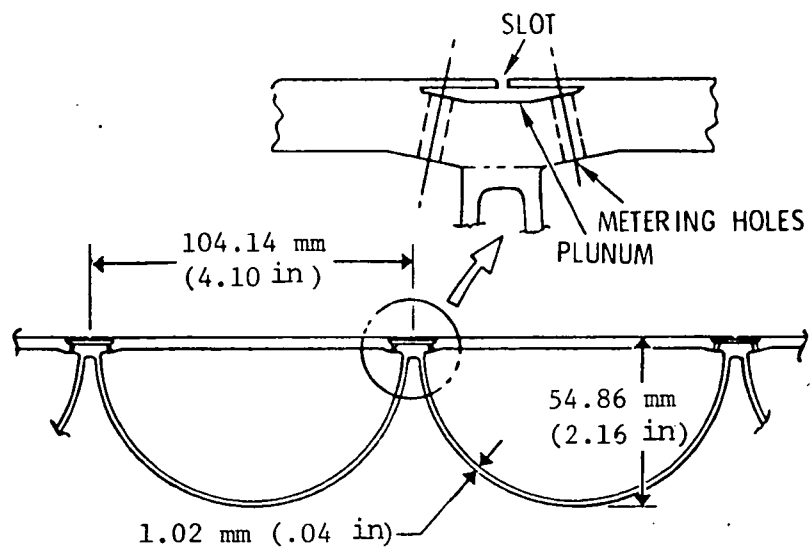


Figure 21

Concept H

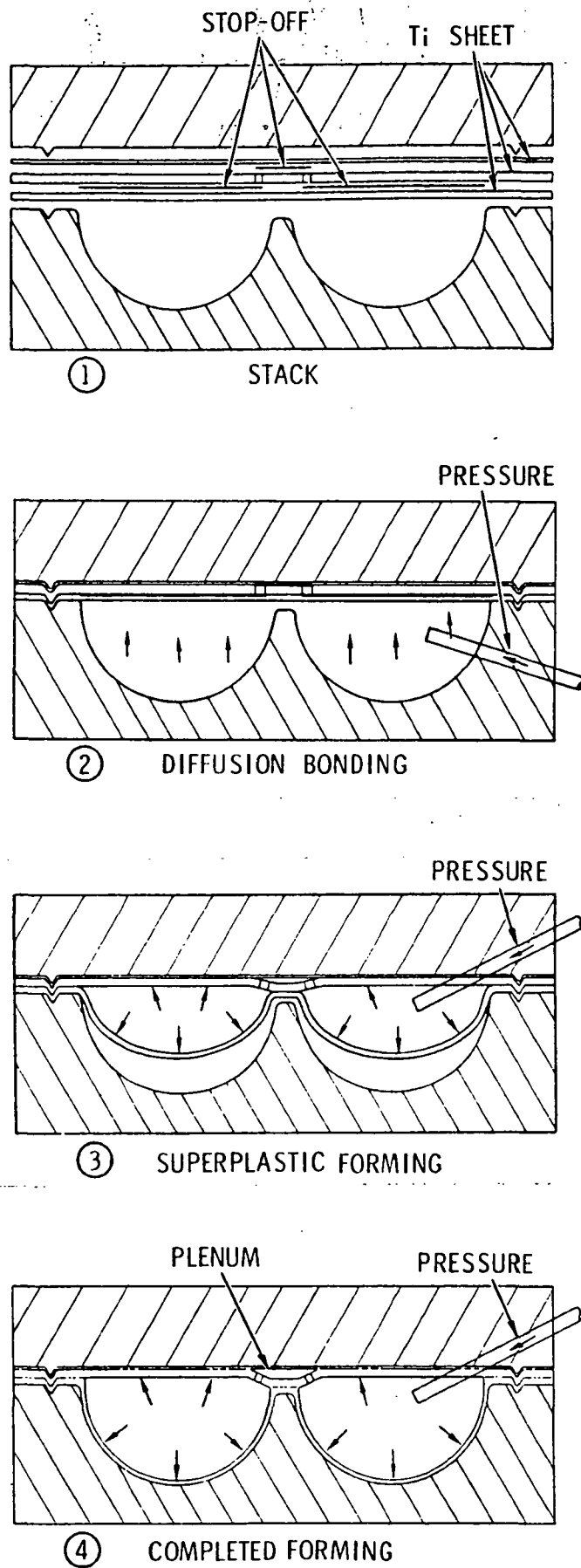


Figure 22

Plenum Forming Process

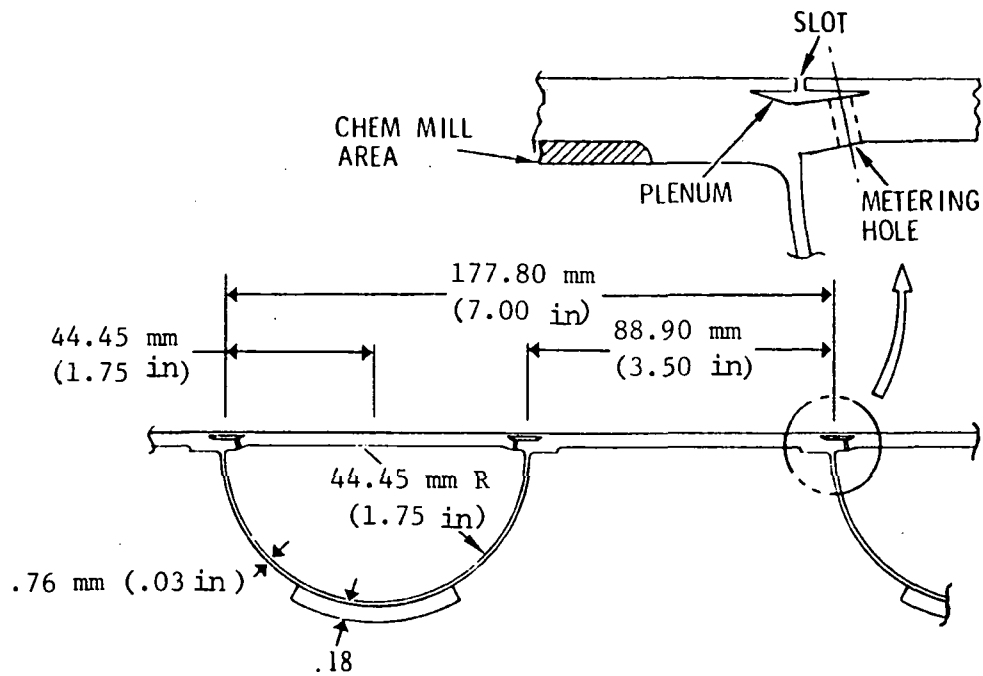


Figure 23

Concept I

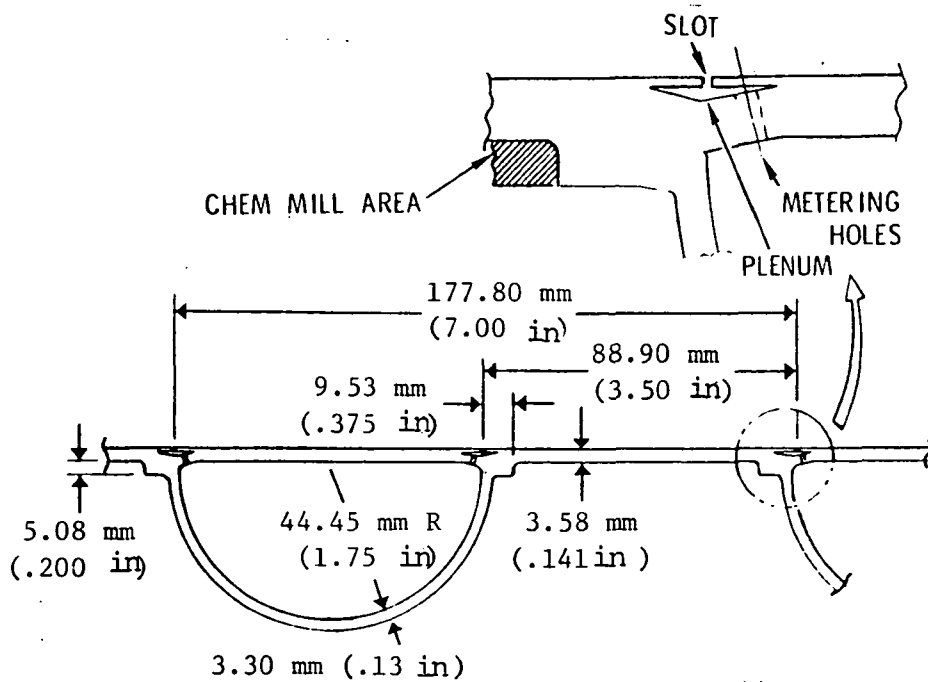


Figure 24

Concept J

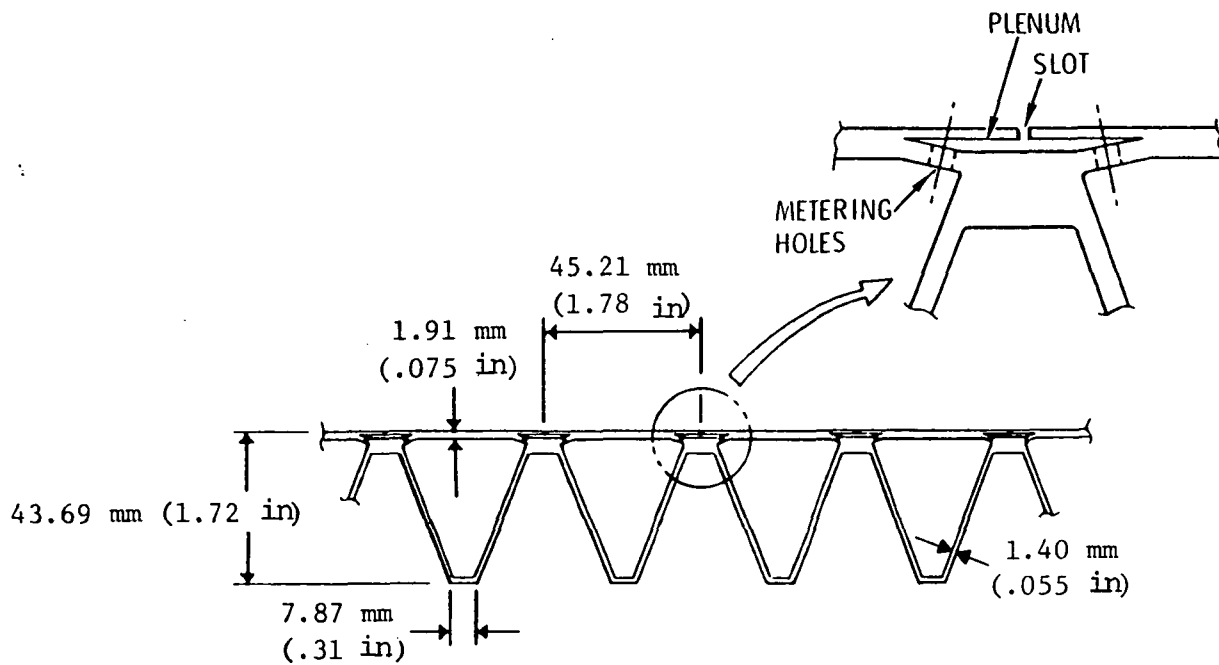


Figure 25

Concept K

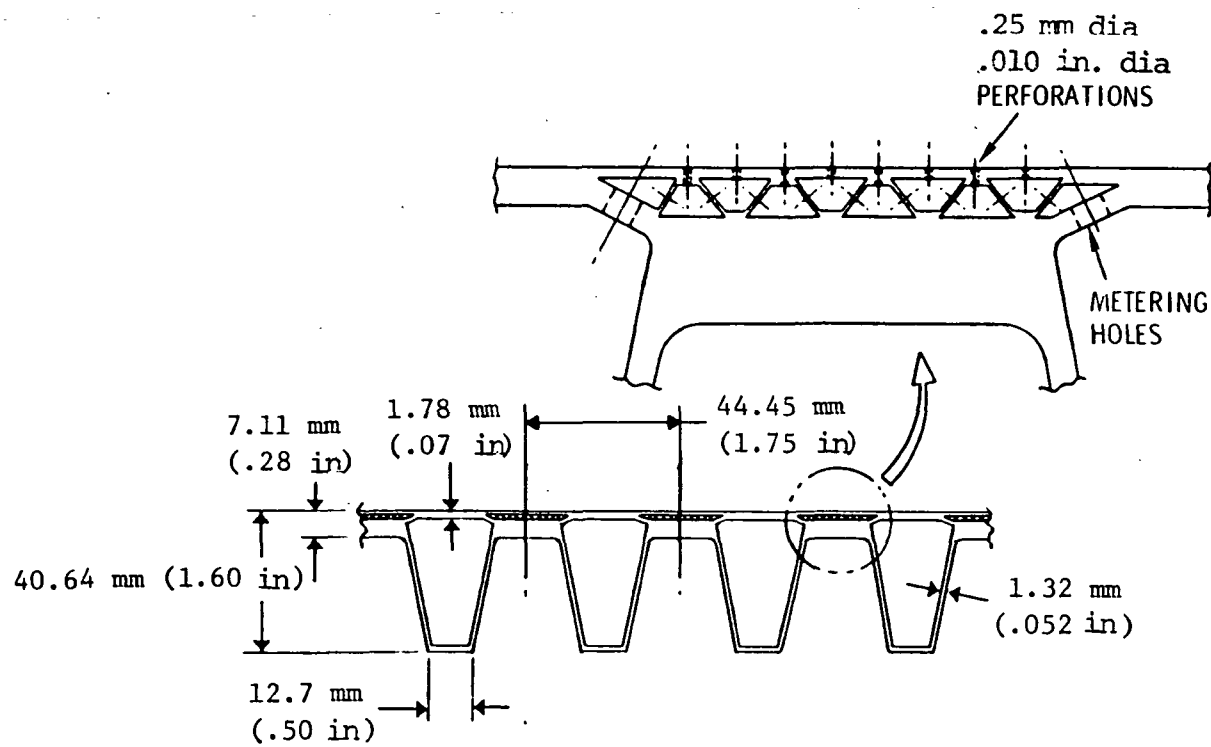


Figure 26

Concept L

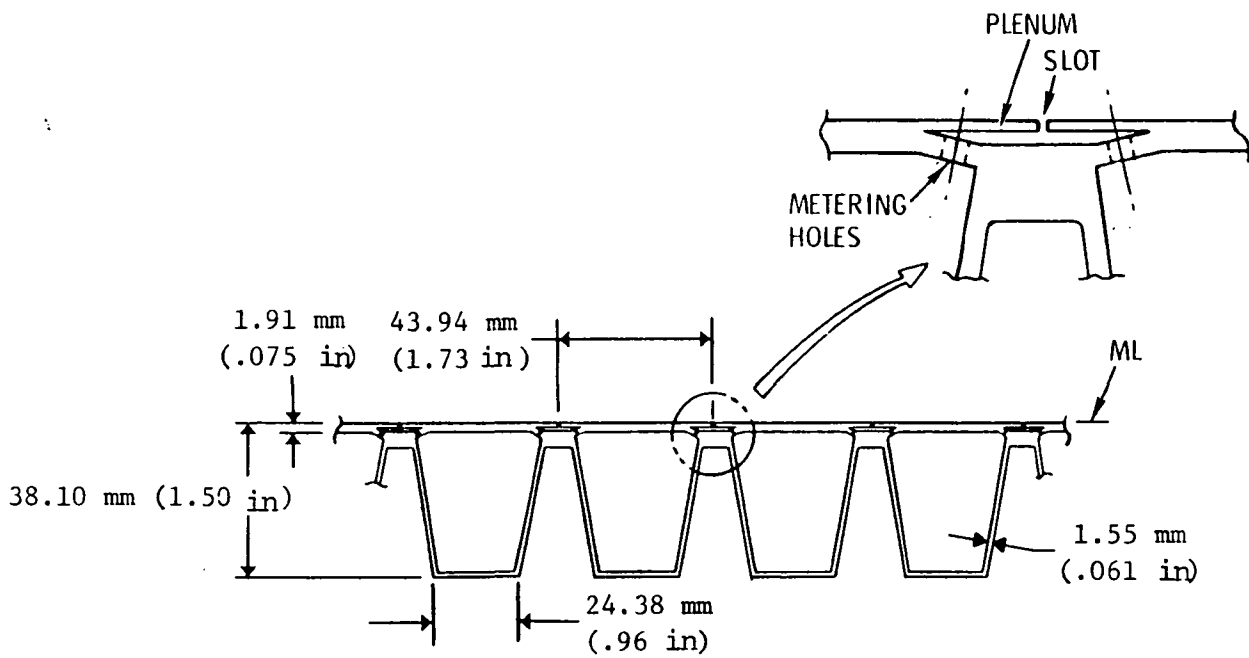


Figure 27

Concept M

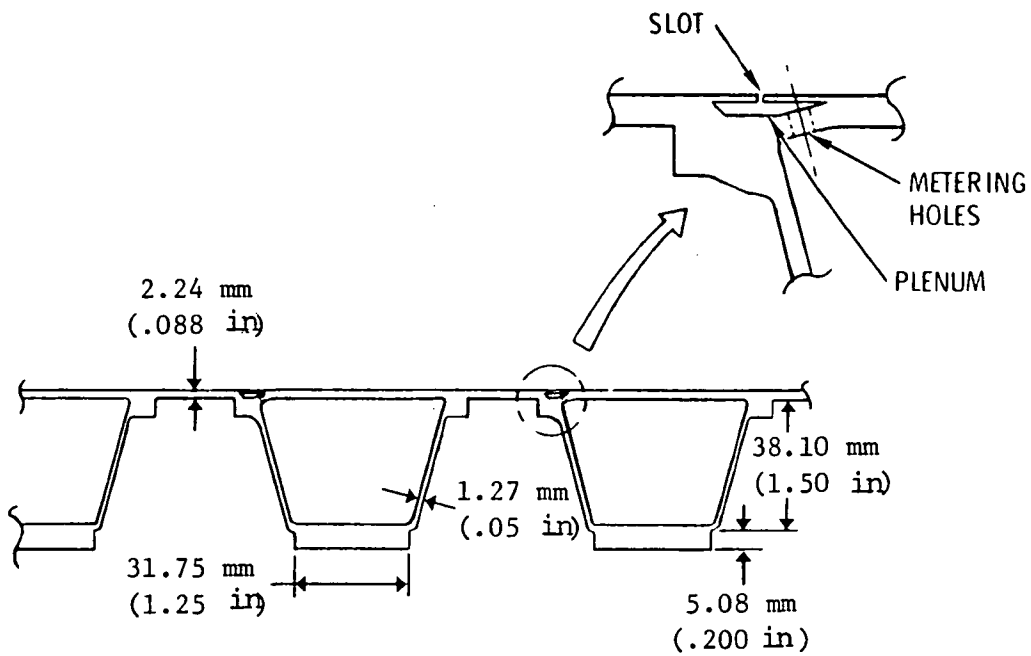
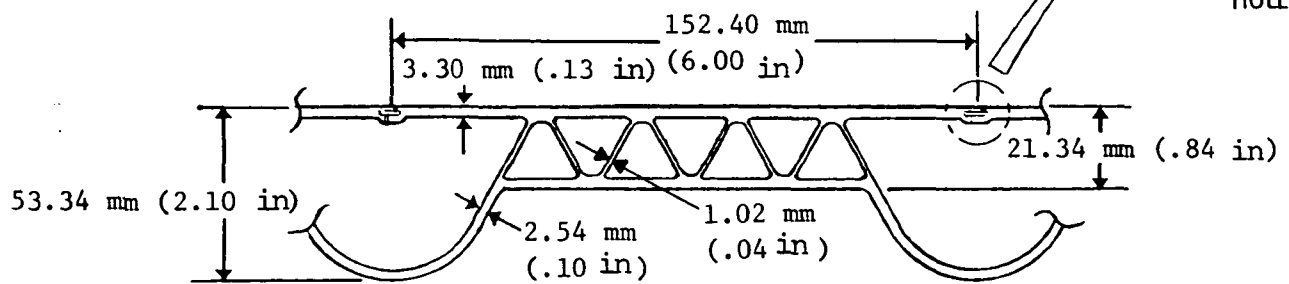
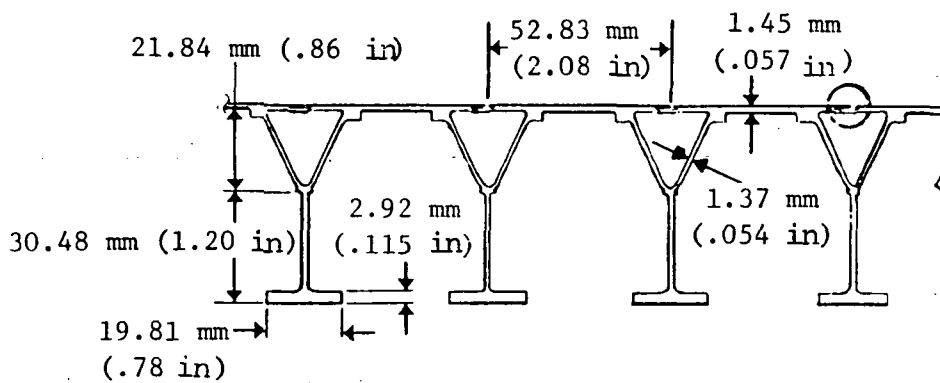
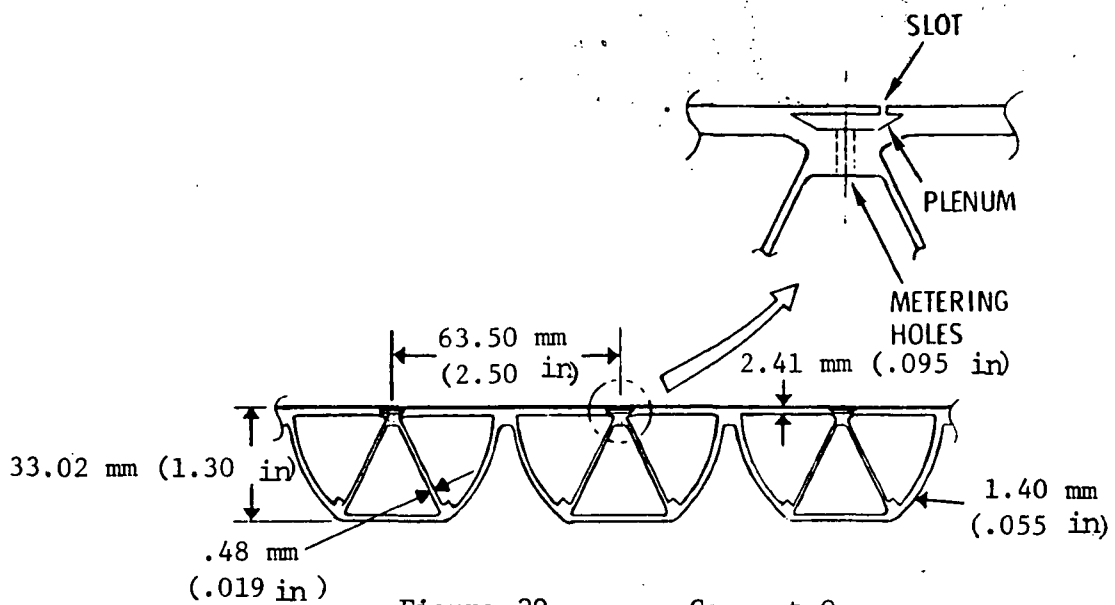


Figure 28

Concept N



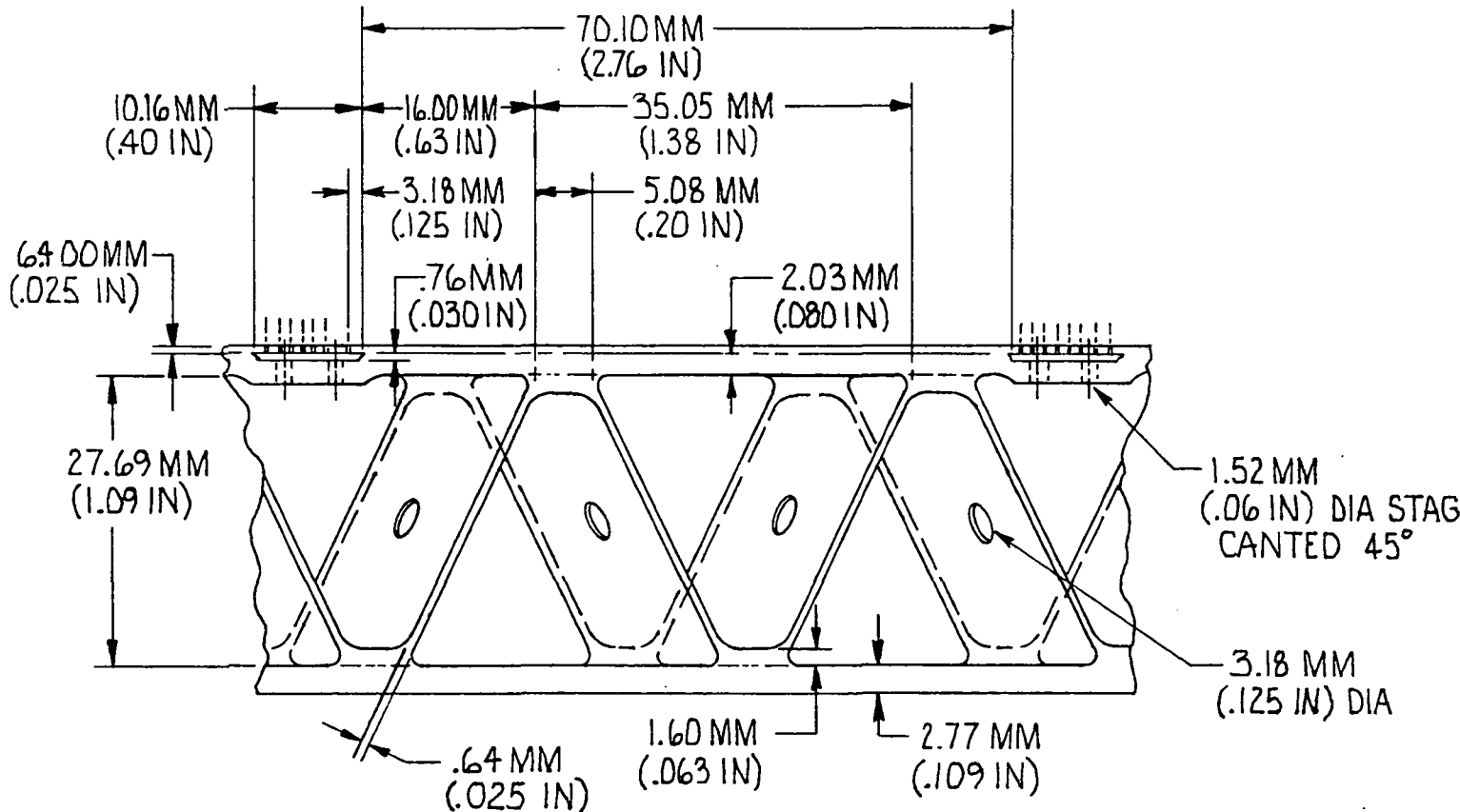
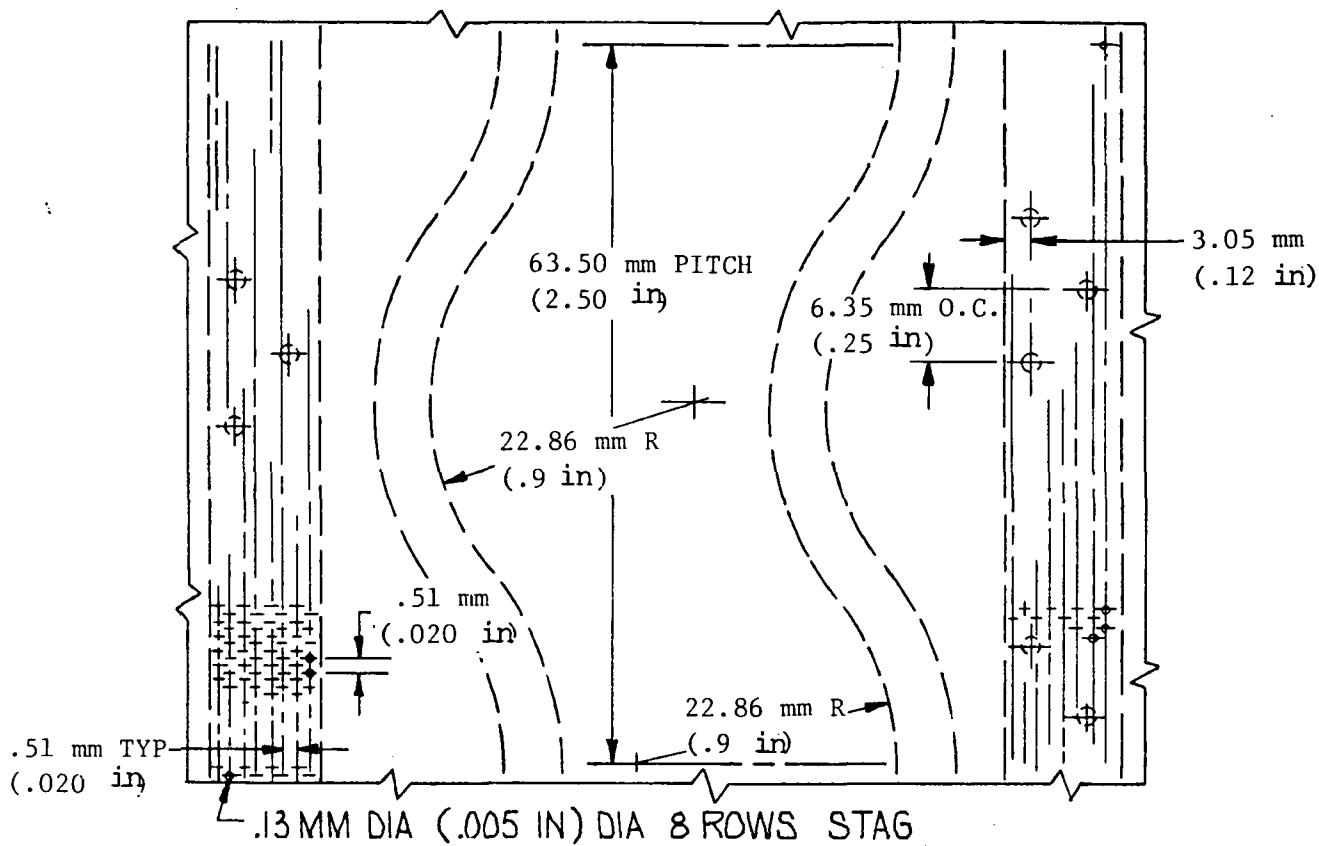


Figure 32 Sine-Wave Truss, Core Perforated

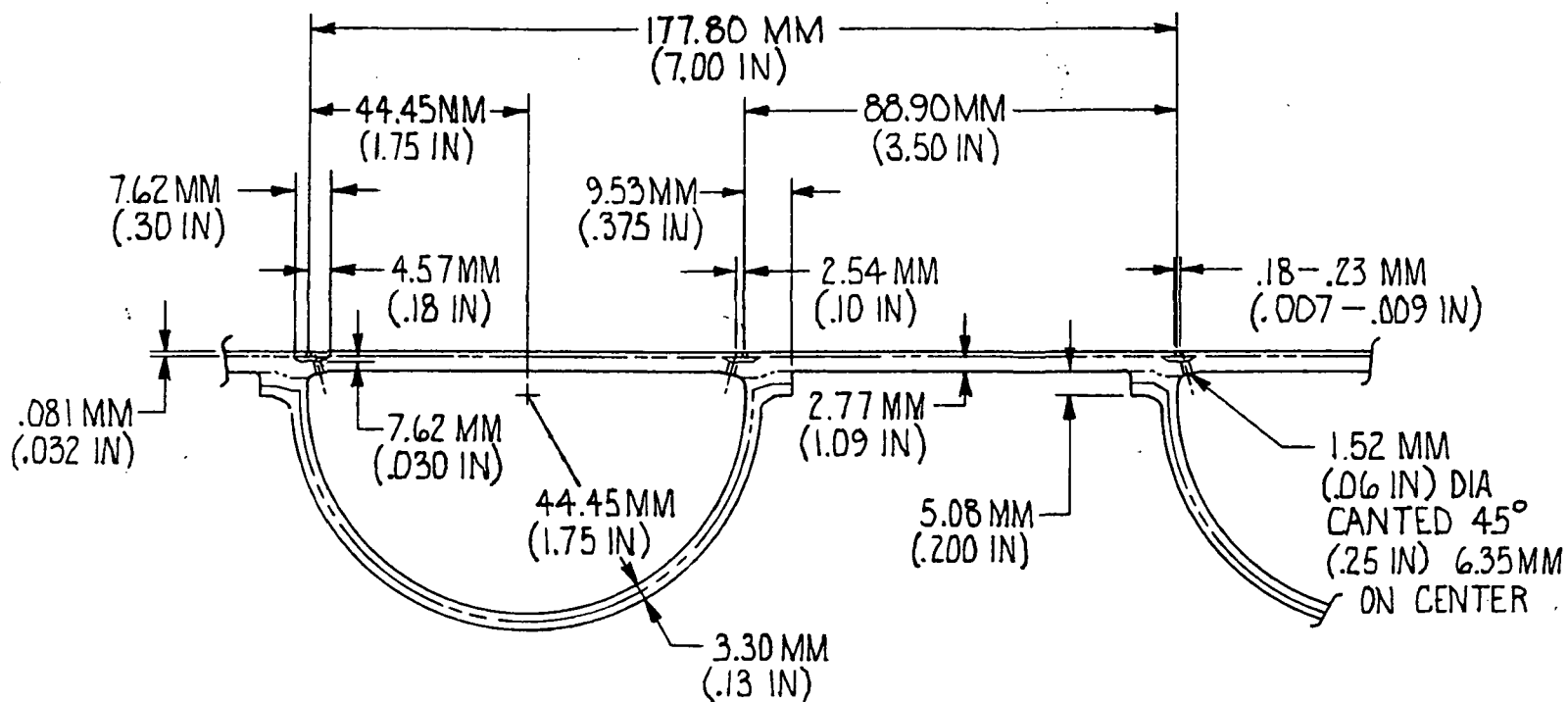


Figure 33 Semi Circular, Semi-Sandwich Panel

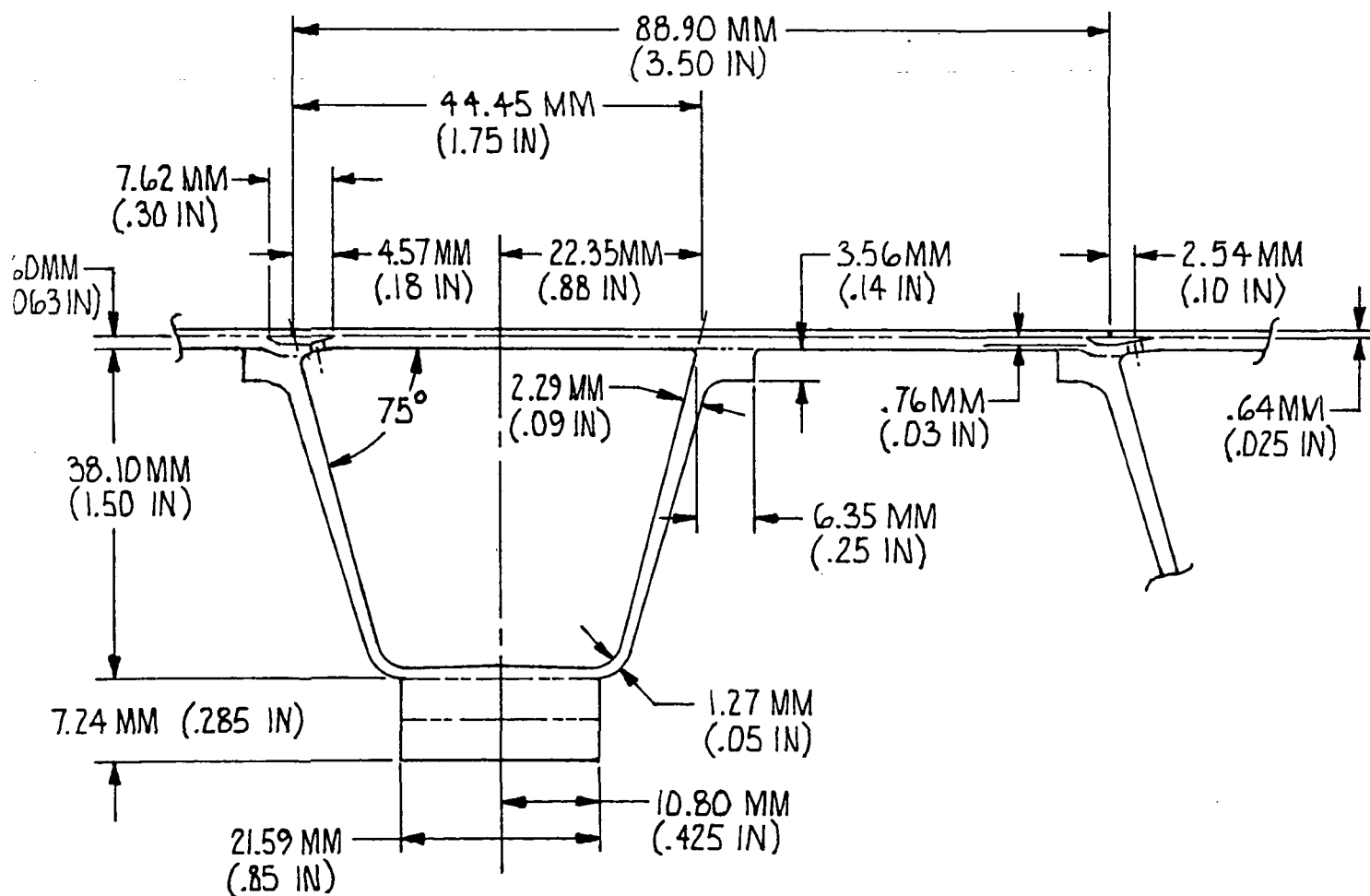


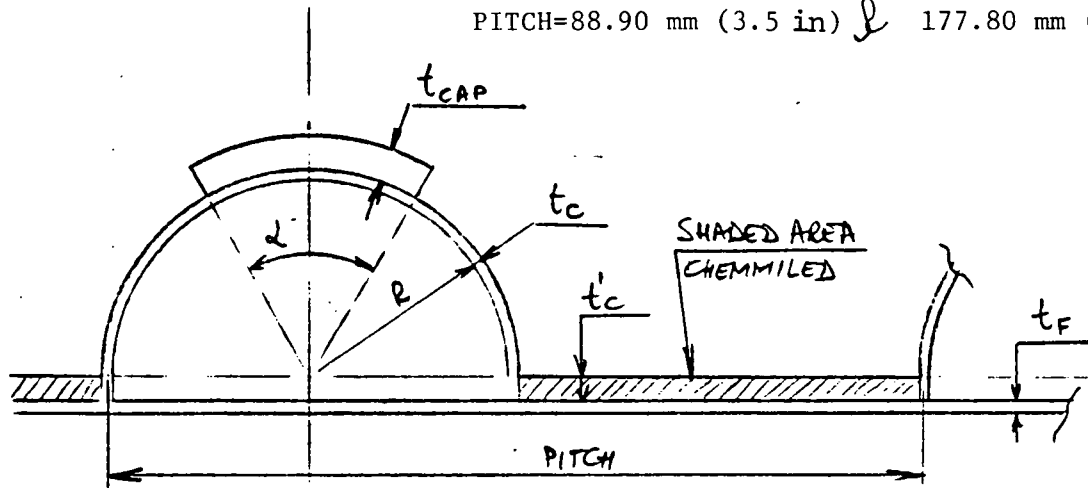
Figure 34 Hat Section, Semi-Sandwich Panel

DESIGN CONSTRAINTS:

$$R = \frac{1}{4} \text{ PITCH}$$

$$\alpha = 60^\circ$$

$$\text{PITCH} = 88.90 \text{ mm (3.5 in)} \text{ \& } 177.80 \text{ mm (7.0 in)}$$



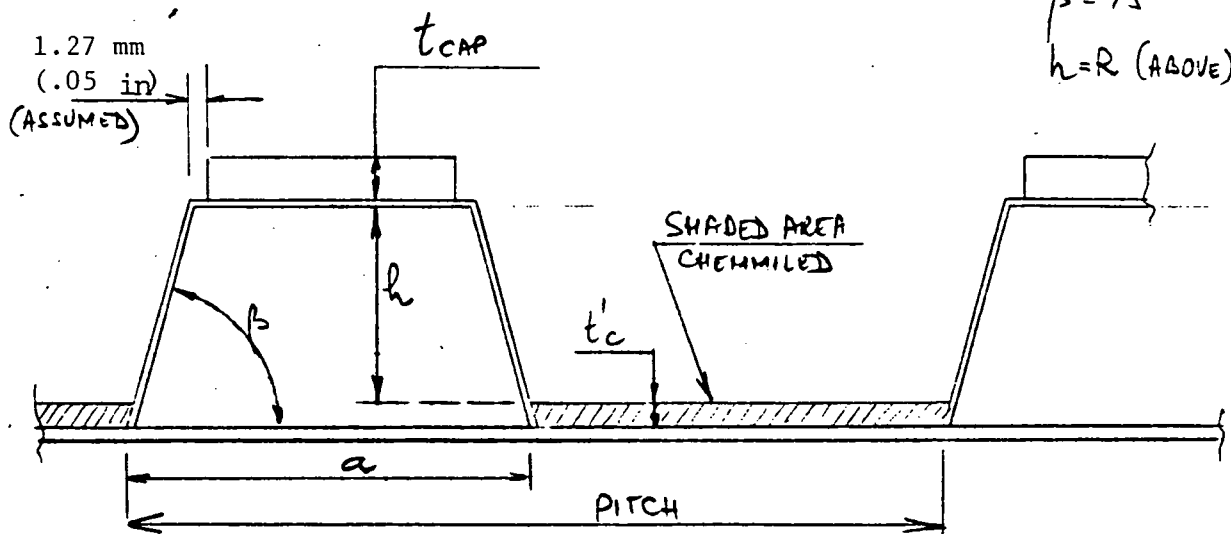
MODIFIED SEMICIRCULAR SEMISANDWICH

DESIGN CONSTRAINTS:

$$\text{PITCH} = 88.90 \text{ mm (3.5 in)} \text{ \& } 177.80 \text{ mm (7.0 in)} ; \alpha = \frac{1}{2} \text{ PITCH}$$

$$\beta = 75^\circ$$

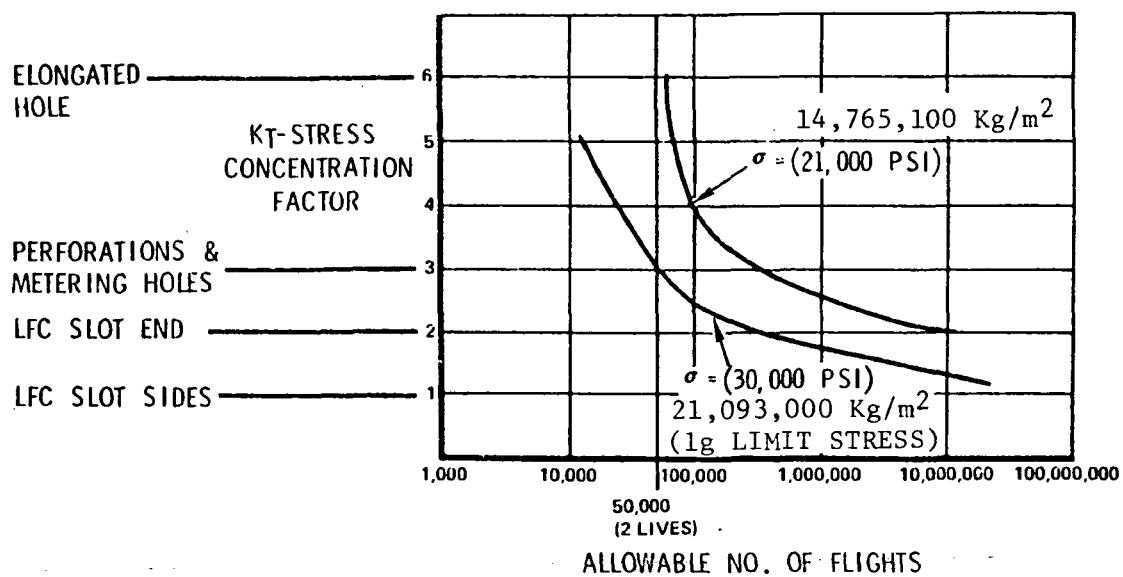
$$h = R \text{ (ABOVE)}$$



MODIFIED TRAPEZOIDAL SEMISANDWICH

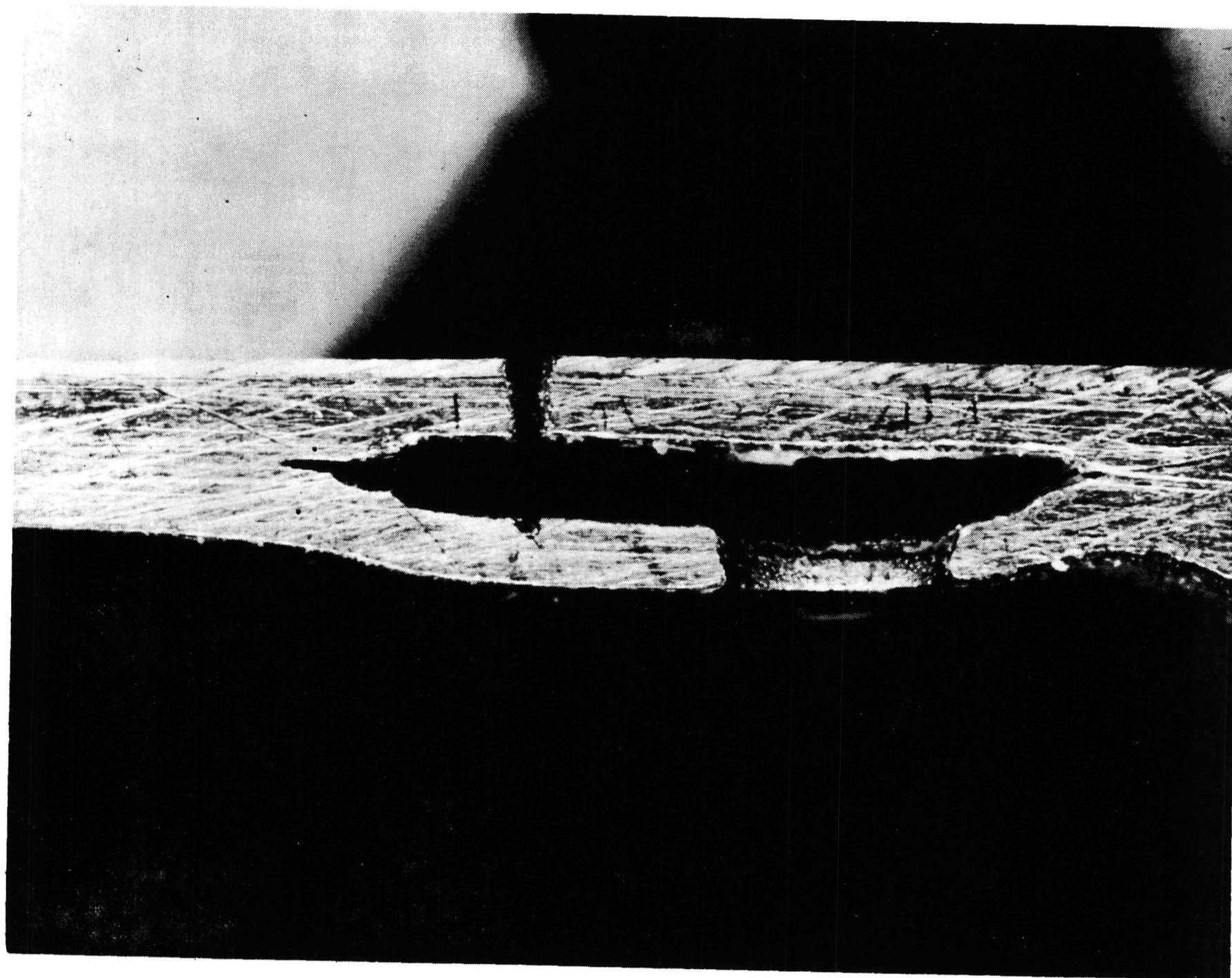
Figure 35

Design Variables



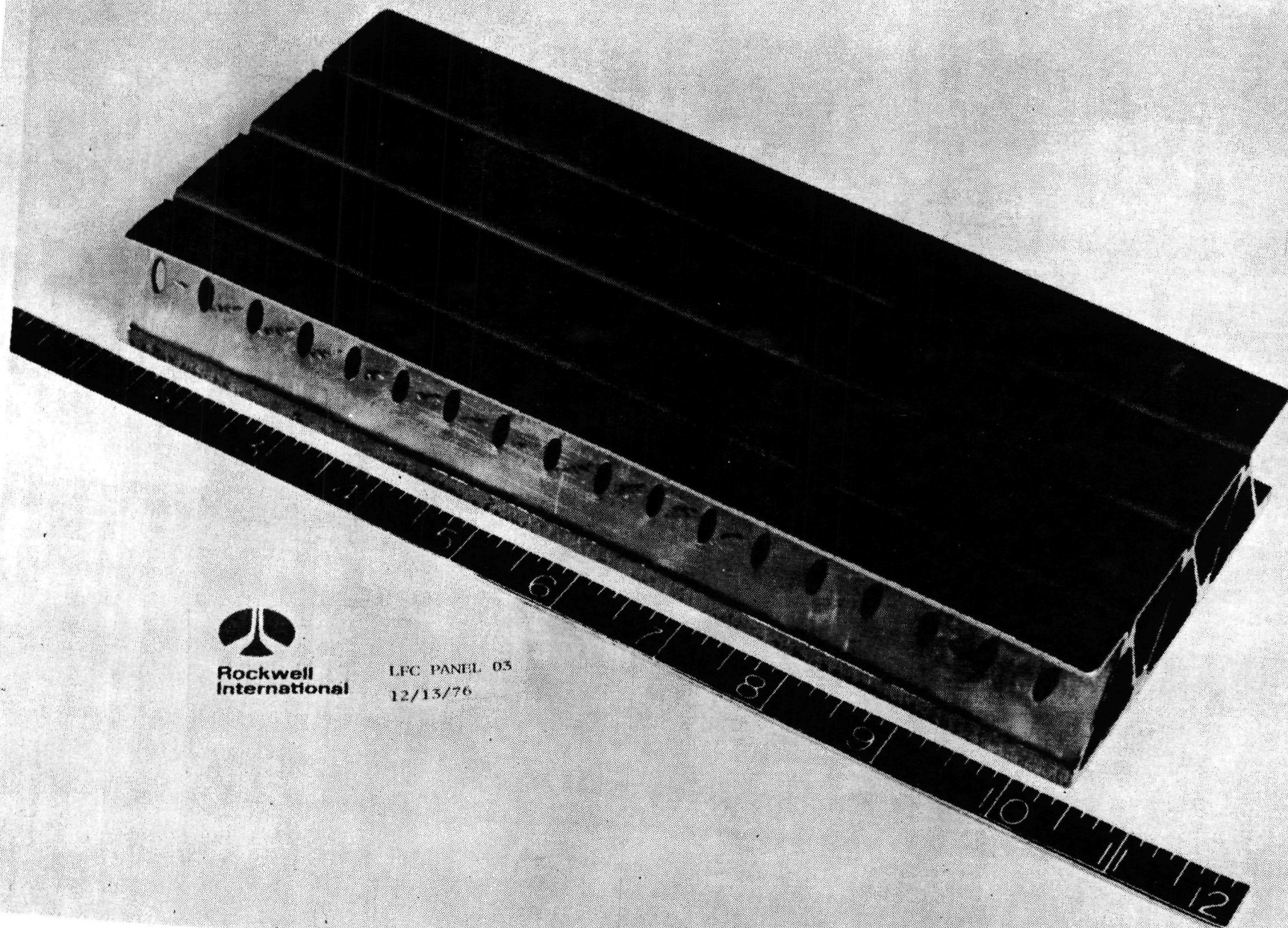
BASIC SPECTRUM INCLUDES ONE G-A-G
CYCLES & 40 MANEUVER/GUST CYCLES

Figure 36 Fatigue Life for LFC Panels



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Figure 37 Plenum Detail



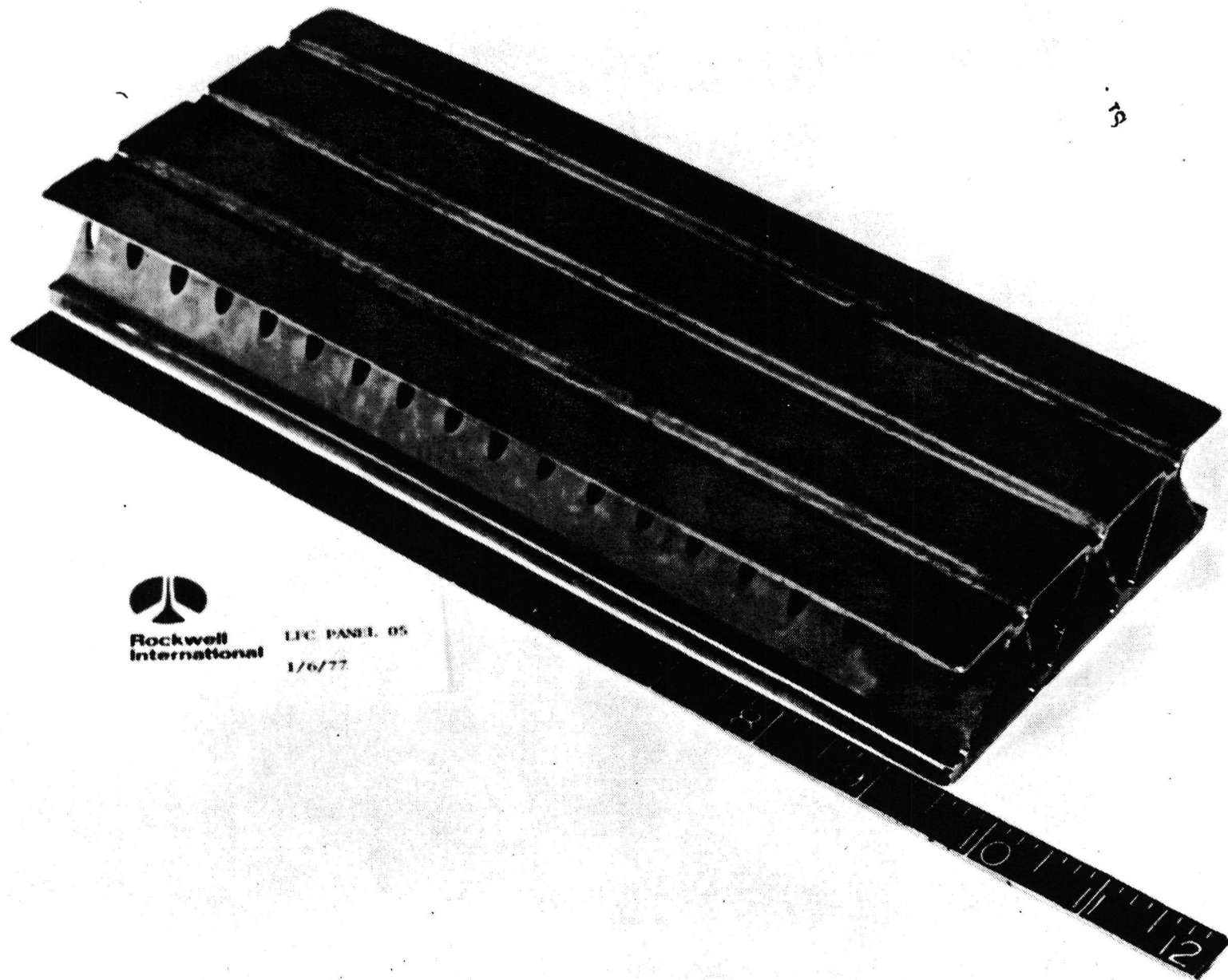
Rockwell
International

LFC PANEL 03
12/13/76

Figure 38

LFC Panel 03

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Rockwell
International

LFC PANEL 05

1/6/77

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Figure 40

LFC Panel 06

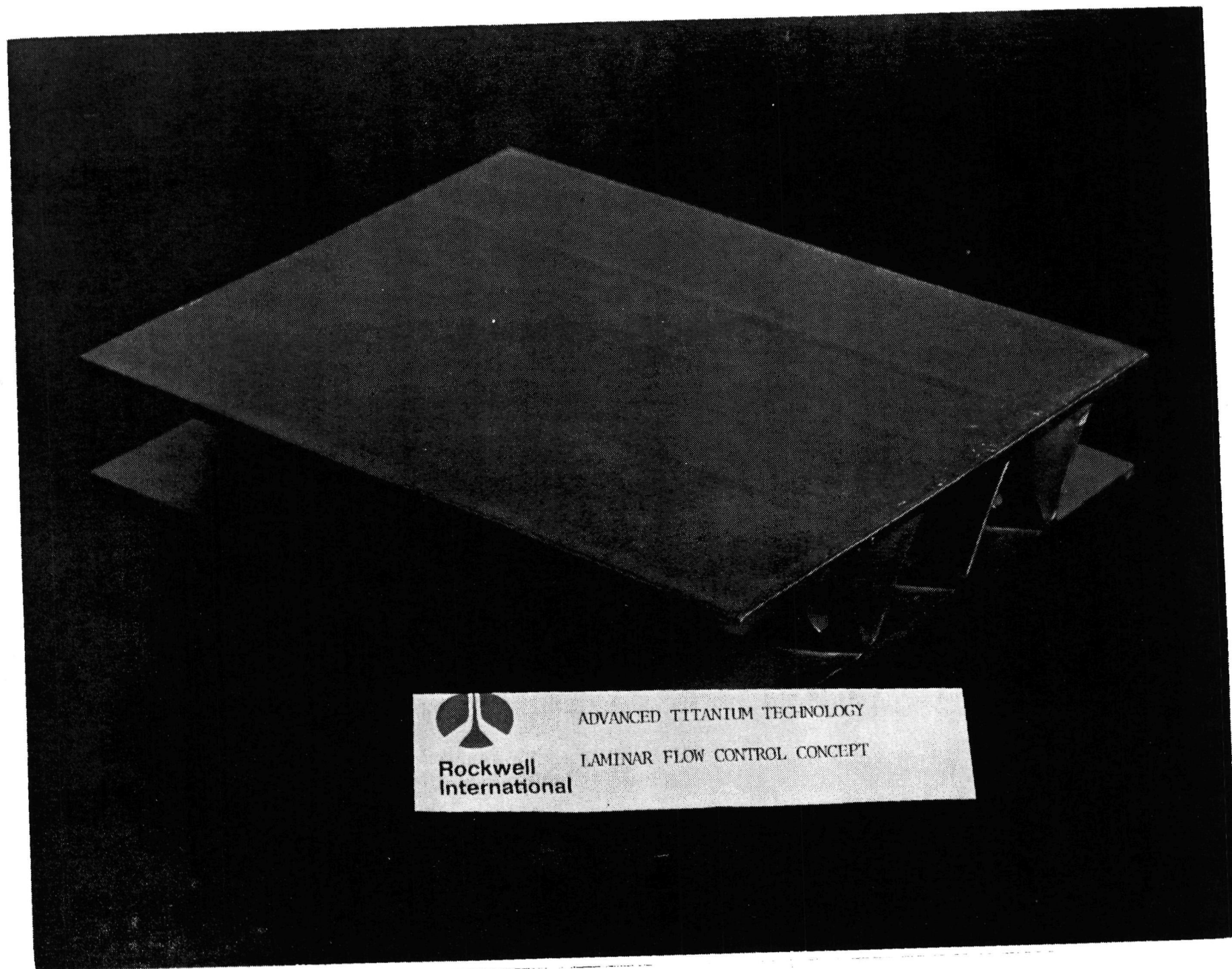


Figure 41 Final Demonstration Panel, Sine Wave Truss Core Sandwich

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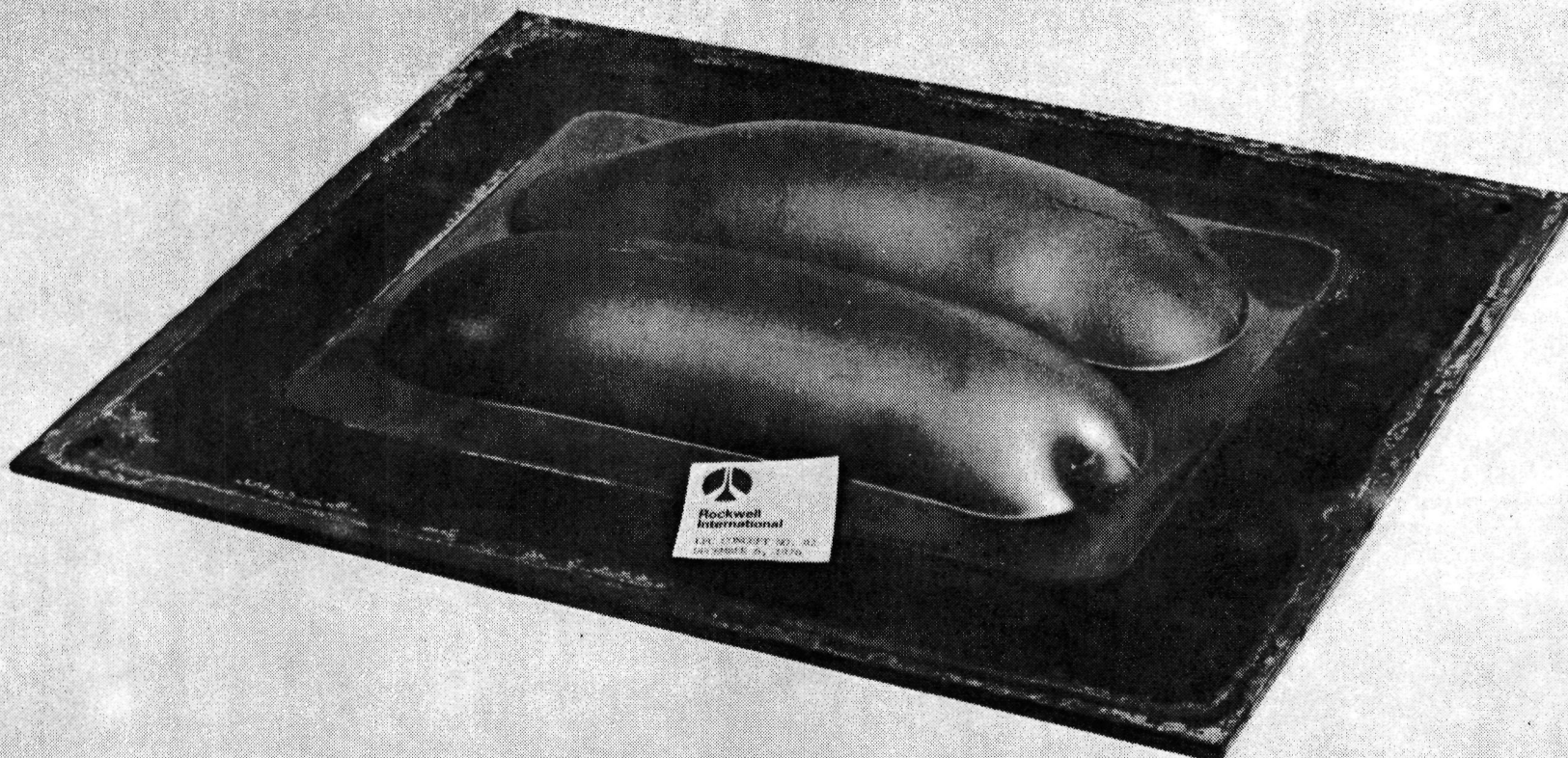
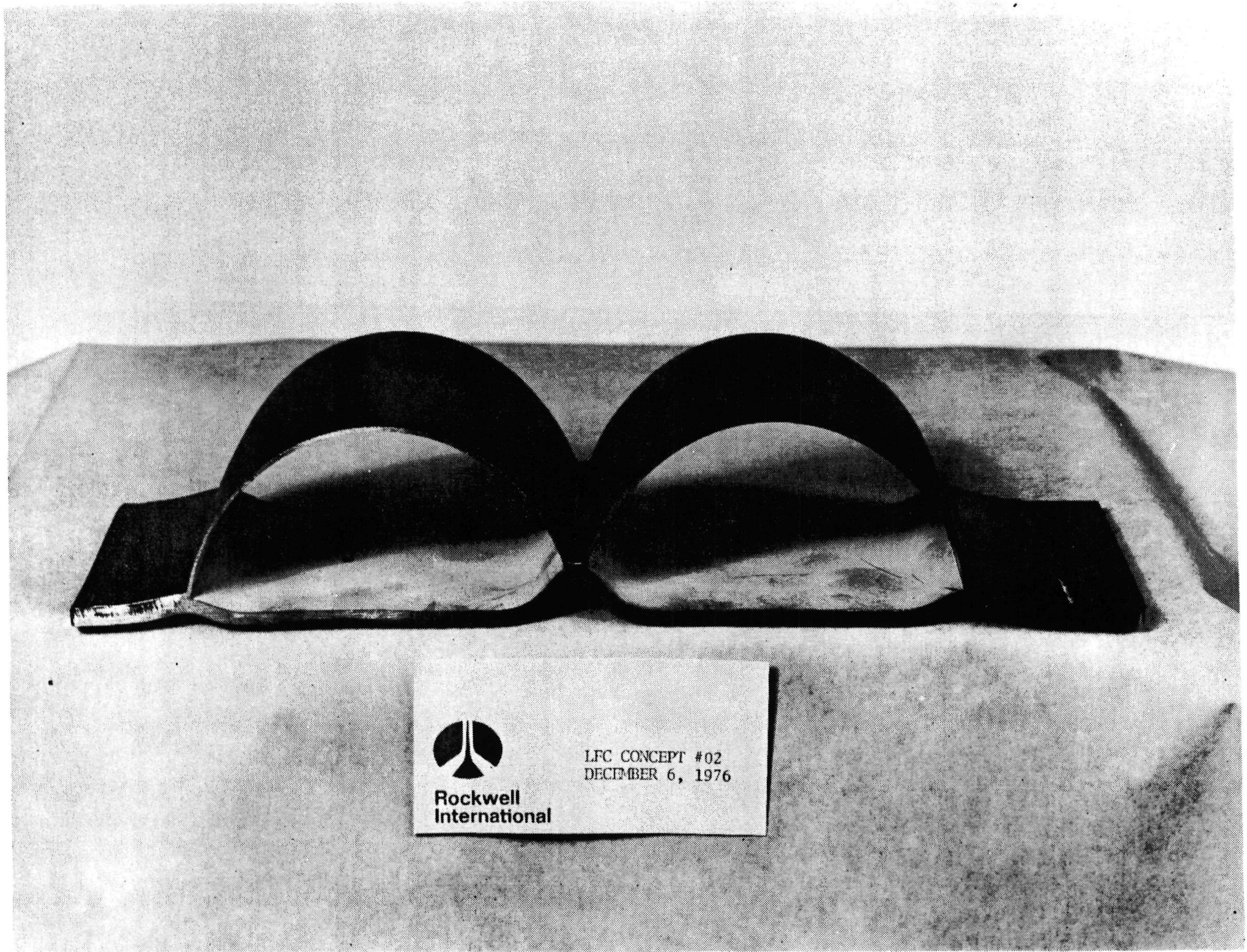


Figure 42

LFC Panel 02, Before Trimming

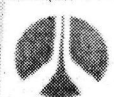
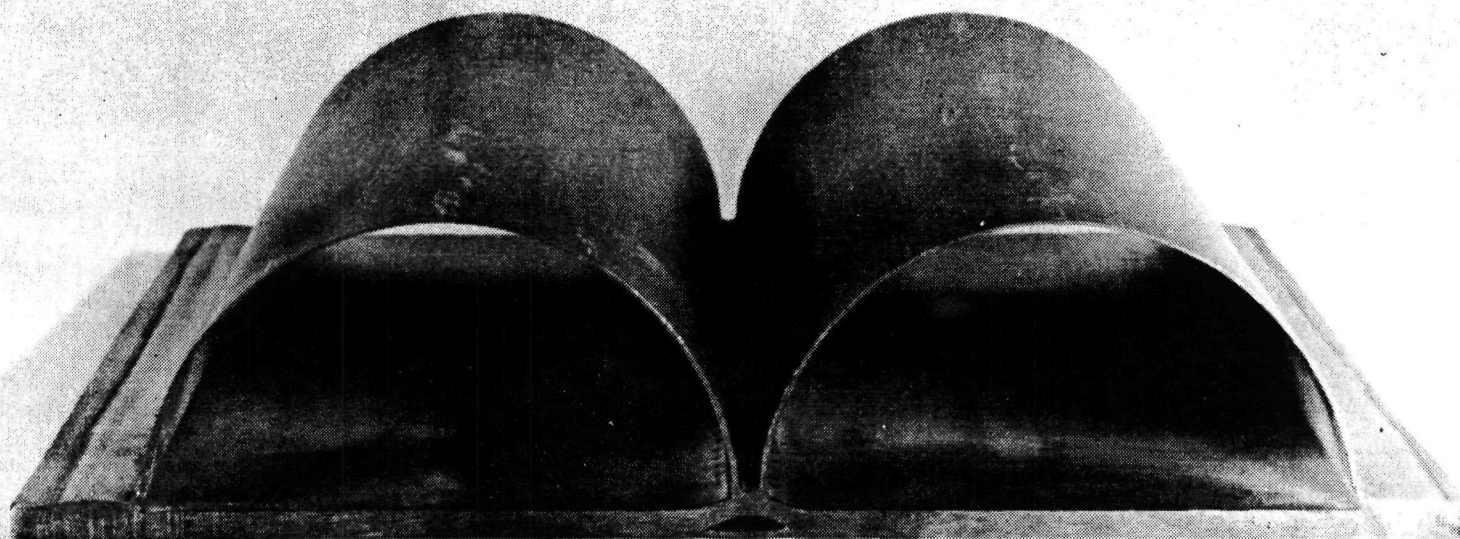
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Rockwell
International

LFC CONCEPT #02
DECEMBER 6, 1976

Figure 43 LFC Panel 02, After Trimming



Rockwell
International

LFC PANEL 04
1/17/77

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Figure 44

LFC Panel 04

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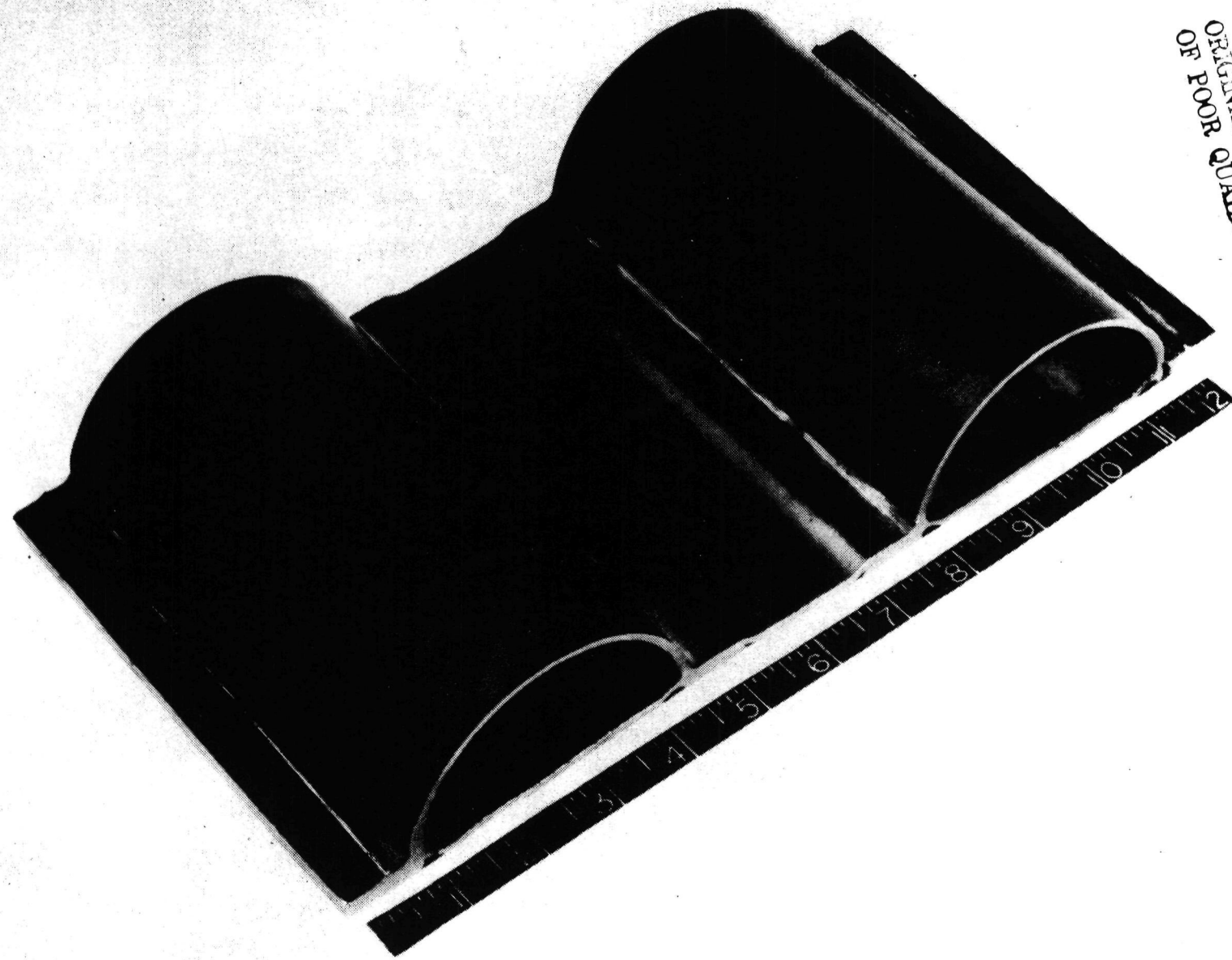


Figure 45

Final Demonstration Panel, Semi-Circular Corrugation

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Figure 46 Final Demonstration Panel - Hat-Stiffened Semi-Sandwich

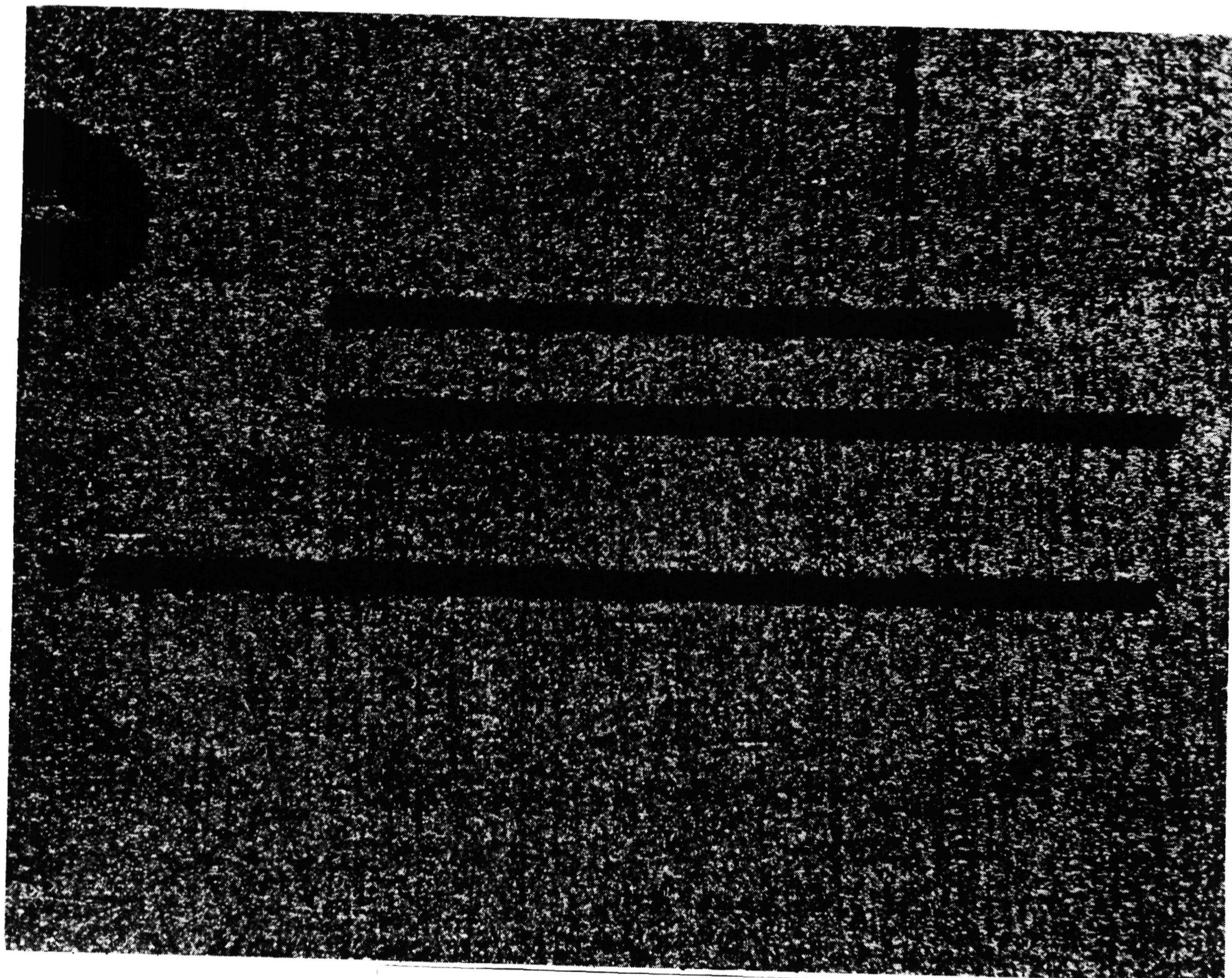


Figure 47 Laser Slots, Moldline Surface

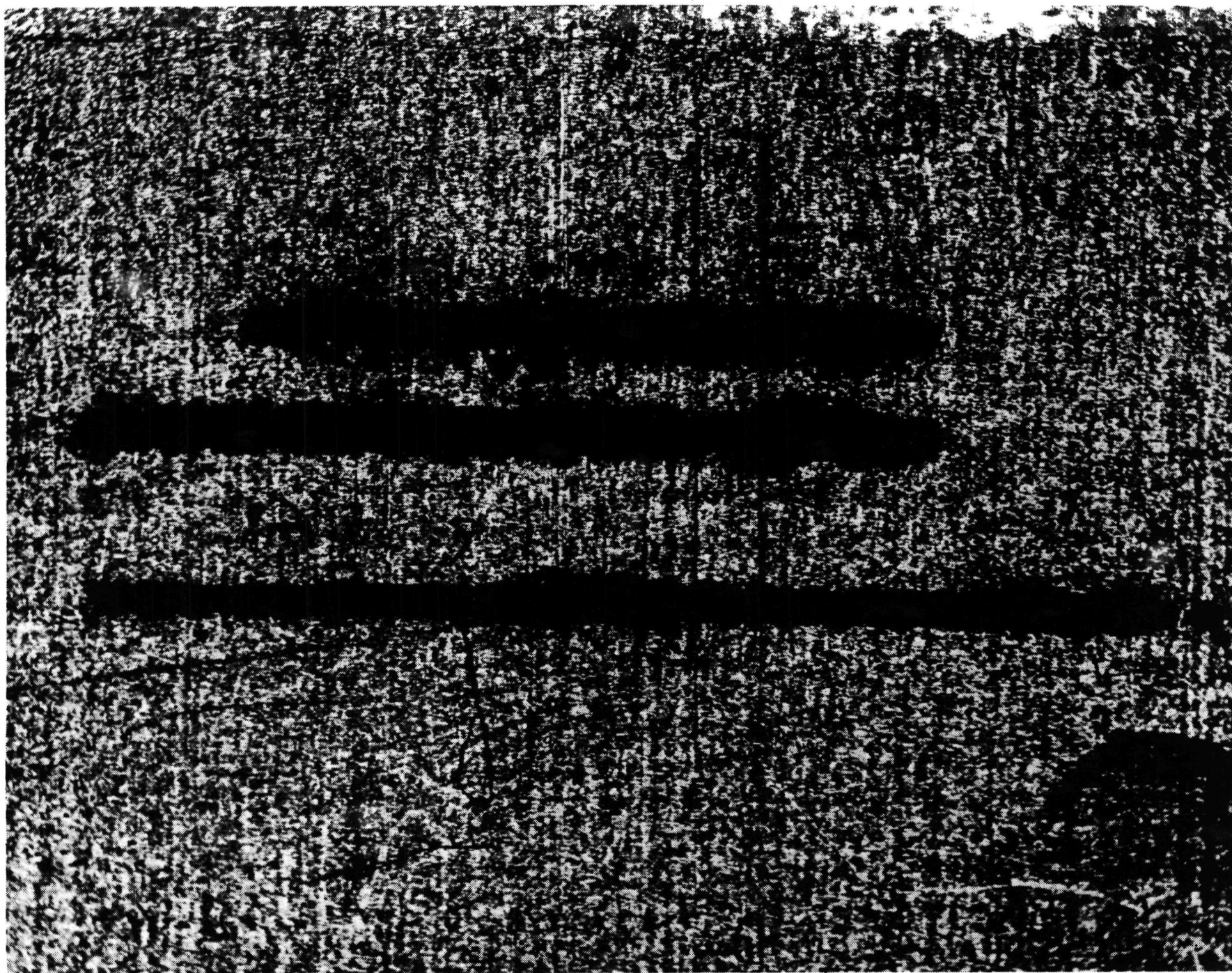
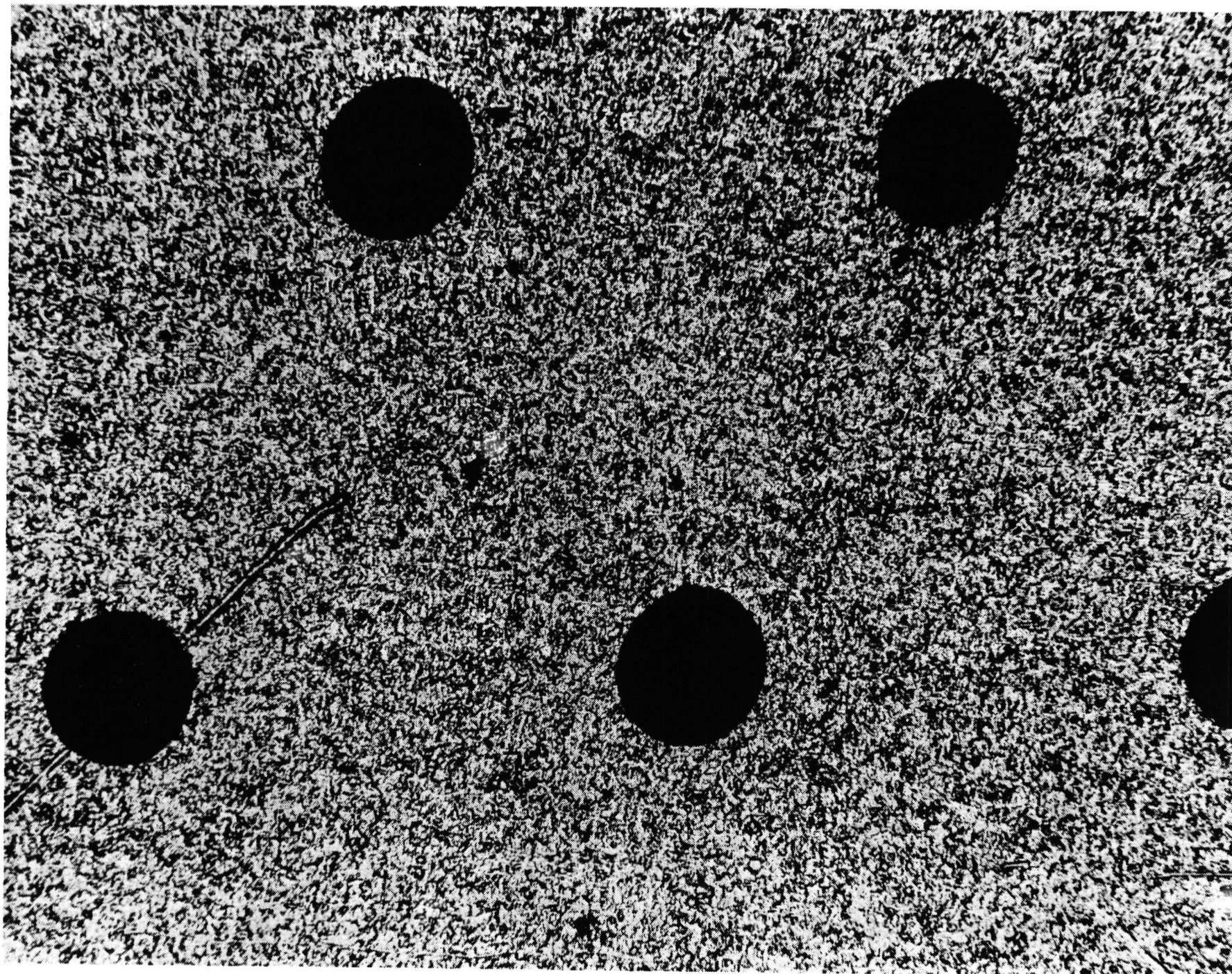


Figure 48

Laser Slots, Inner Surface

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Figure 49 . Electron Beam Holes, INNER Surface at 200X

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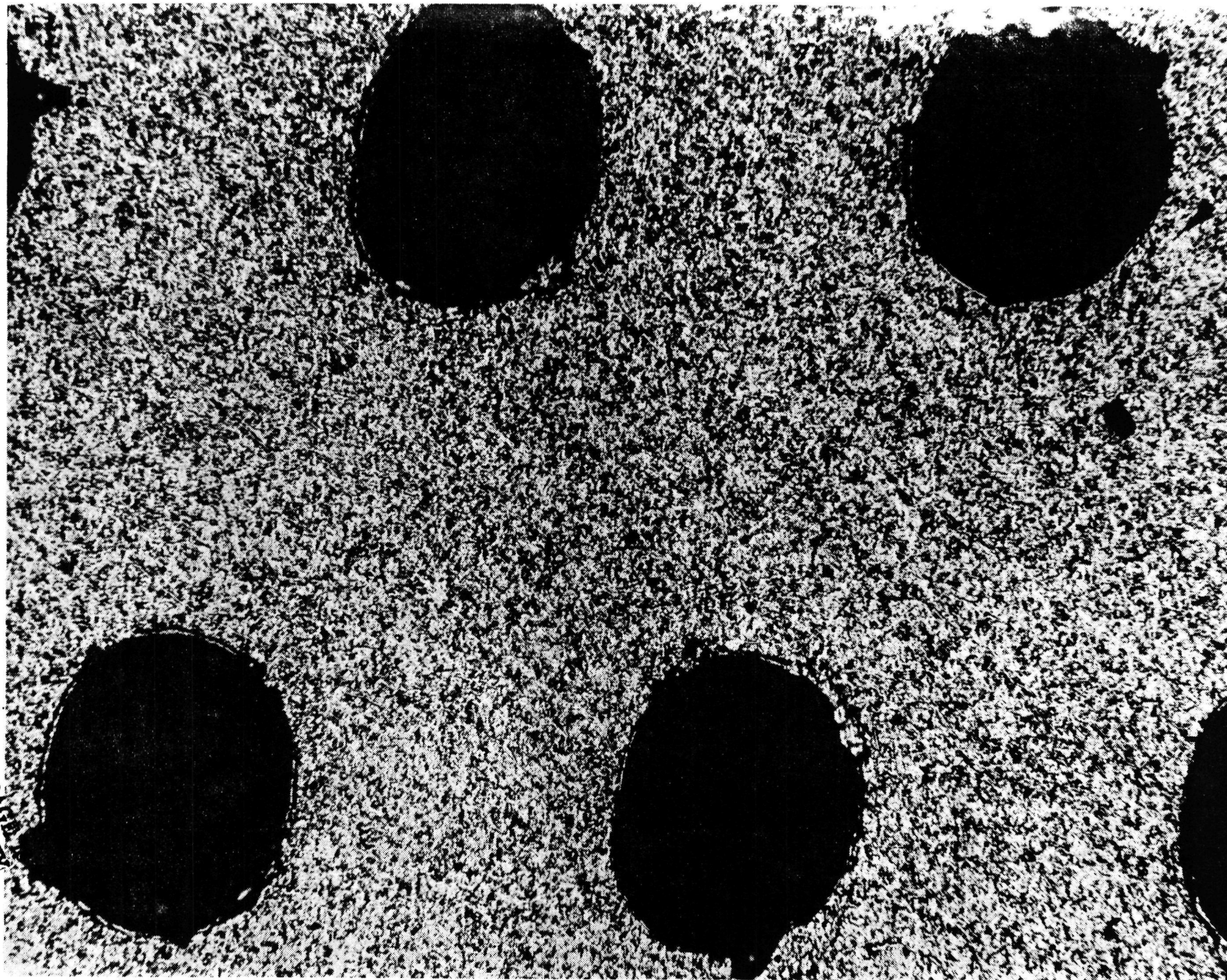


Figure 50

Electron Beam Holes, OUTER Surface at 200X

	HAT SECTION SEMI-SANDWICH	SEMI-CIRCULAR SEMI-SANDWICH	SINEWAVE TRUSS SANDWICH
AREA/ INCH ($\bar{t}$)	6.223 MM^2/MM (.245 $\text{IN.}^2/\text{IN.}$)	6.655 MM^2/MM (.262 $\text{IN.}^2/\text{IN.}$)	7.035 MM^2/MM (.277 $\text{IN.}^2/\text{IN.}$)
WEIGHT	LOW	LOW	HIGHER
PRODUCTION COST	LOW	LOWEST	LOW
VISUAL INSPECTION	YES	YES	SOME
MAINTENANCE	GOOD	GOOD	MORE DIFFICULT
AIRLOAD RIB ATTACHMENT	GOOD	MORE DIFFICULT	GOOD
PANEL SPLICE	GOOD	MORE DIFFICULT	MORE DIFFICULT
TAILORABLE GEOMETRY	GOOD	FAIR	FAIR
DUCT AREA	22.61 MM^2 (.89 IN.^2)	20.07 MM^2 (.79 IN.^2)	25.91 MM^2 (1.02 IN.^2)

Figure 51

Selected LFC Design Comparisons

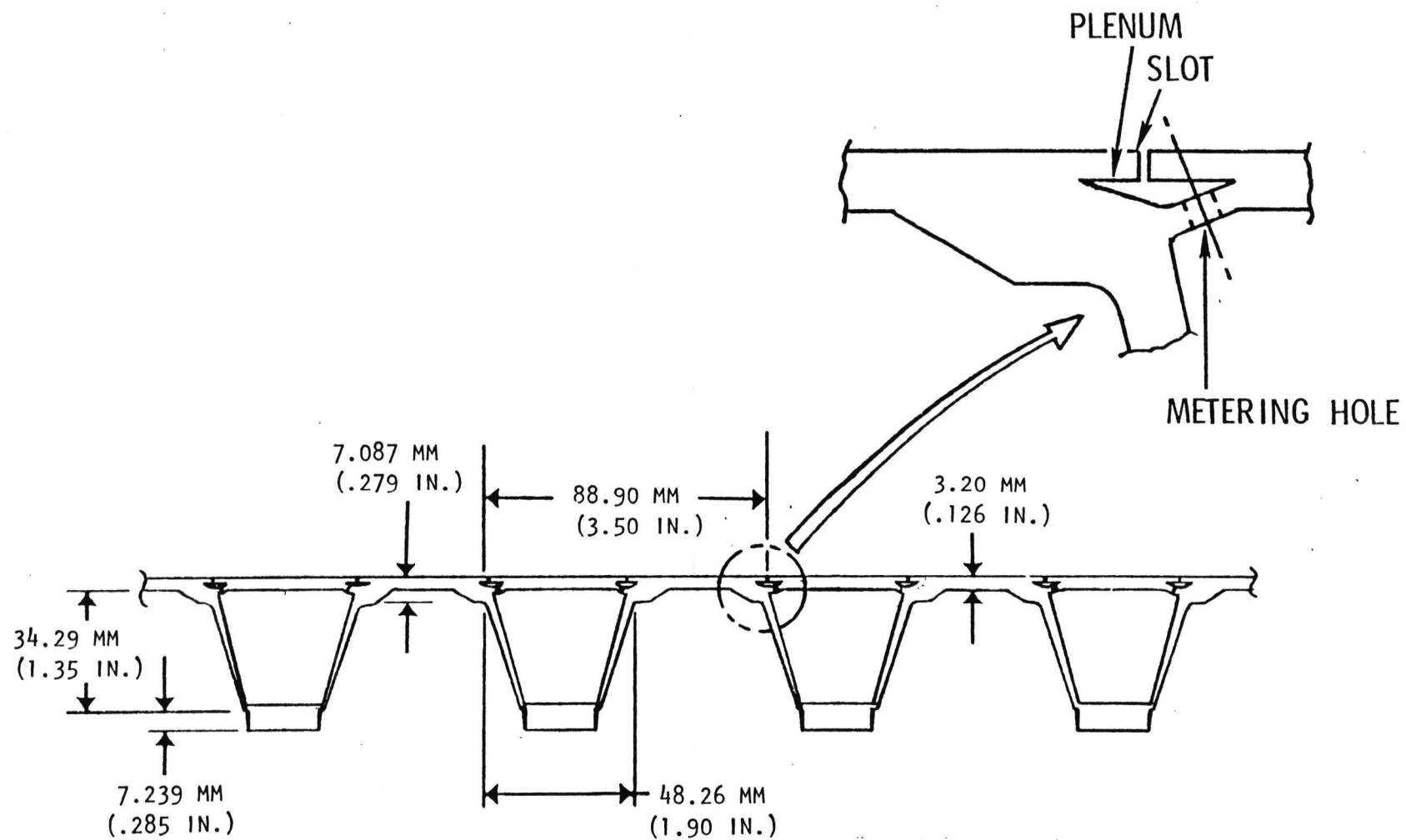
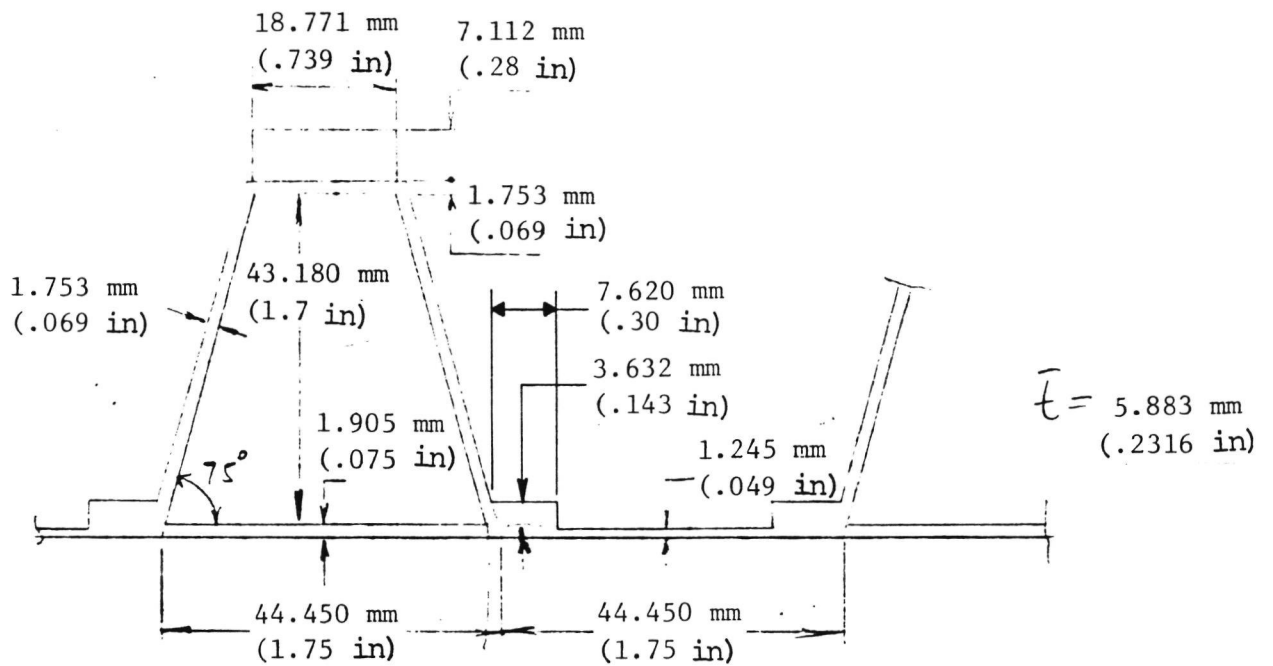


Figure 52

Hat Stiffened Skin
Fabrication Development Specimen



$$N_x = 432170 \text{ Kg/m (24200 \#/in)}$$

$$F_{c_y} = F_{t_u} = 117 \text{ KSI}$$

Material 6Al-4V Titanium

Spar Spacing = 635 mm (25 in)

Figure 53 Final Optimized Section

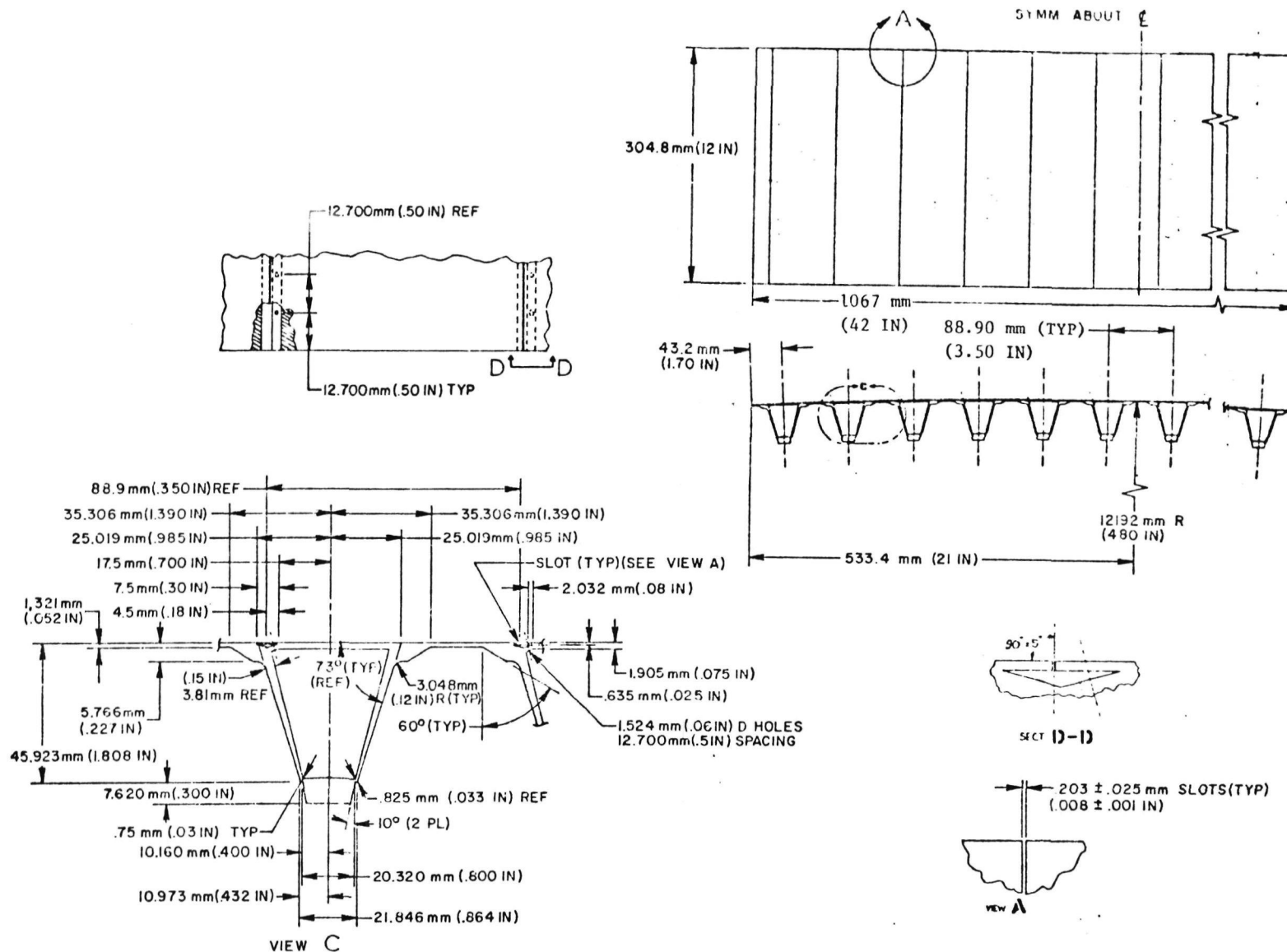


Figure 54 Feasibility Panel Design

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Figure 55 Feasibility Panel SPF/DB Tooling

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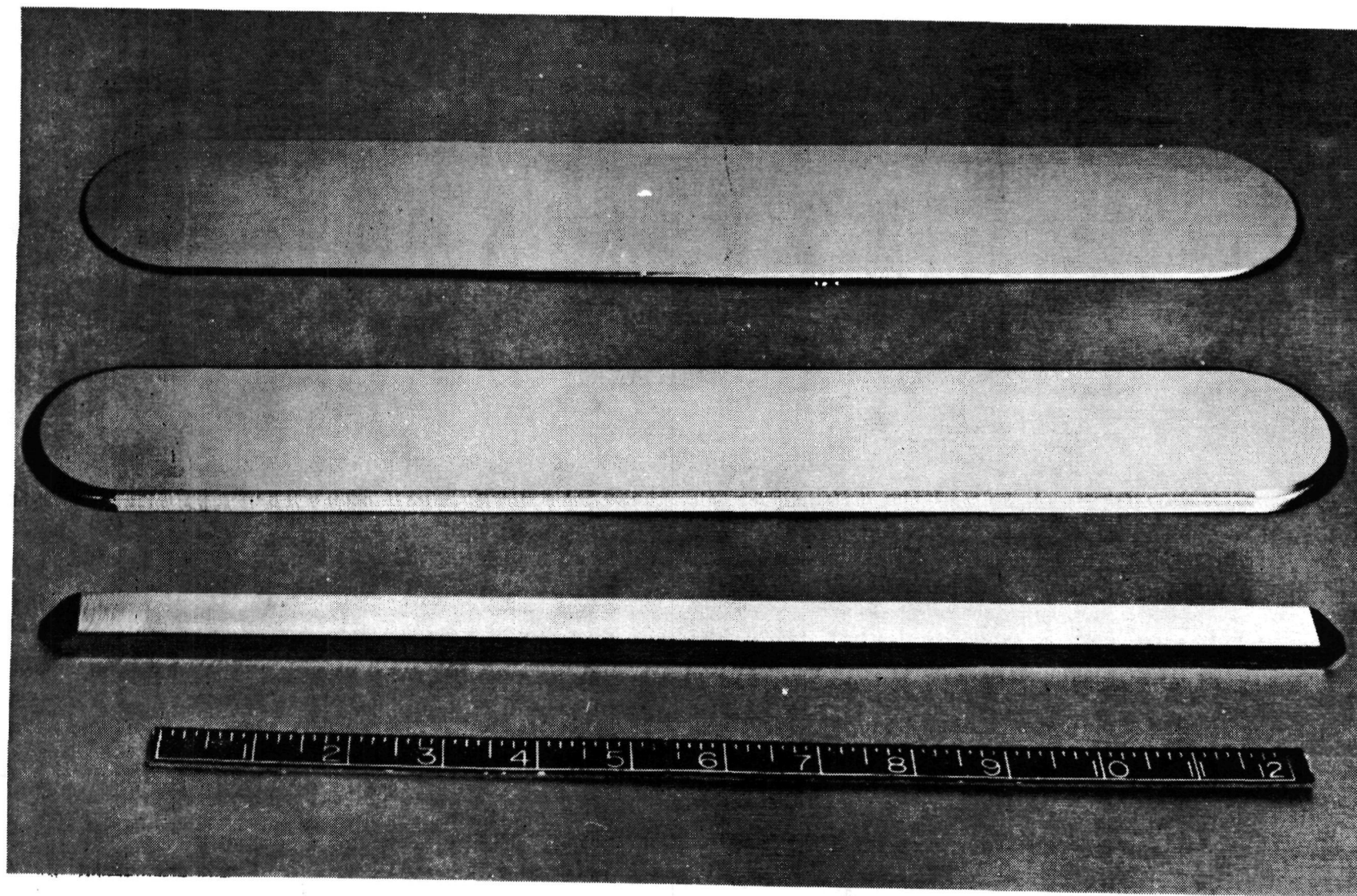
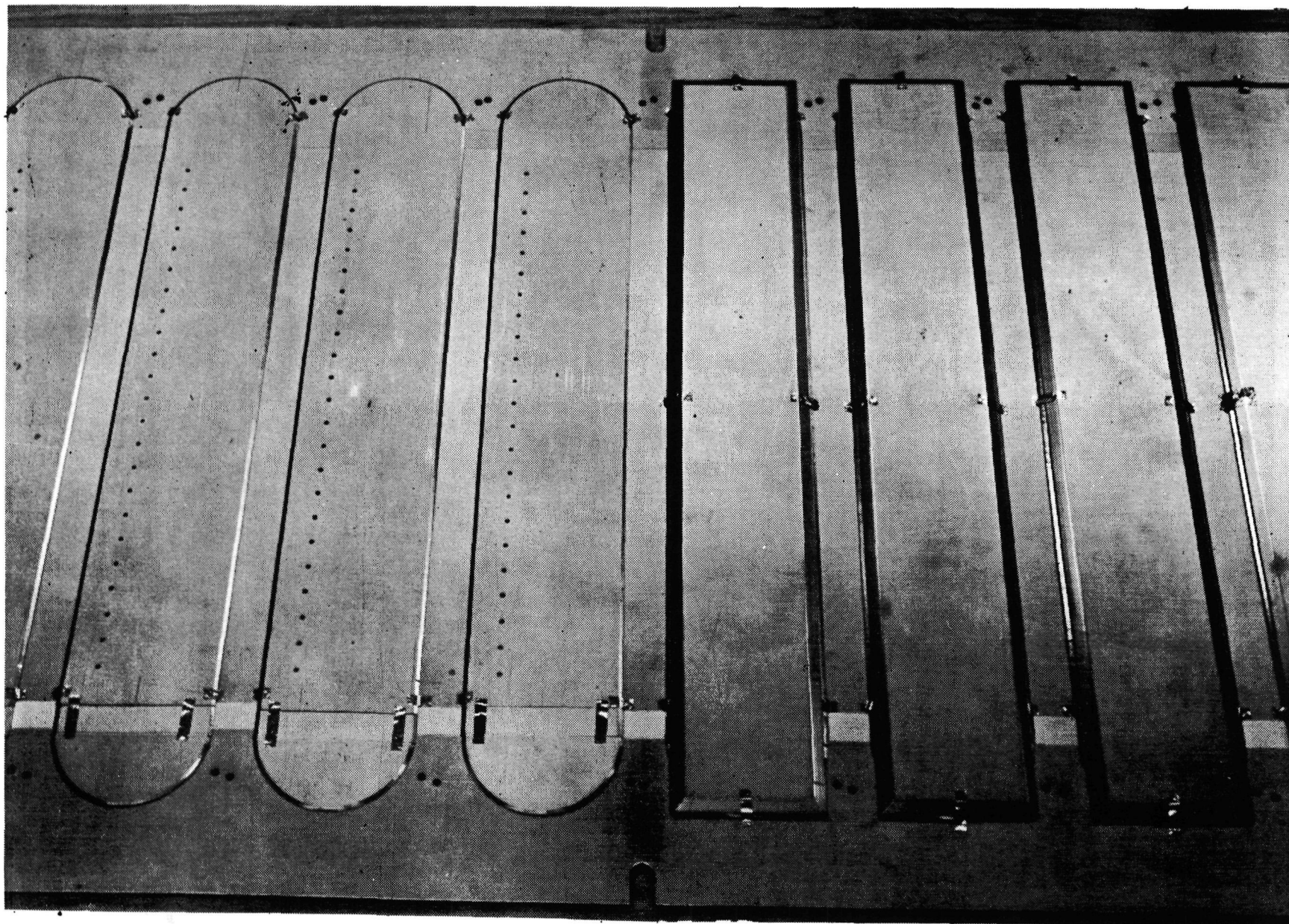


Figure 56. Detail Machined Parts for Panel



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Figure 57 Detail Parts During Assembly

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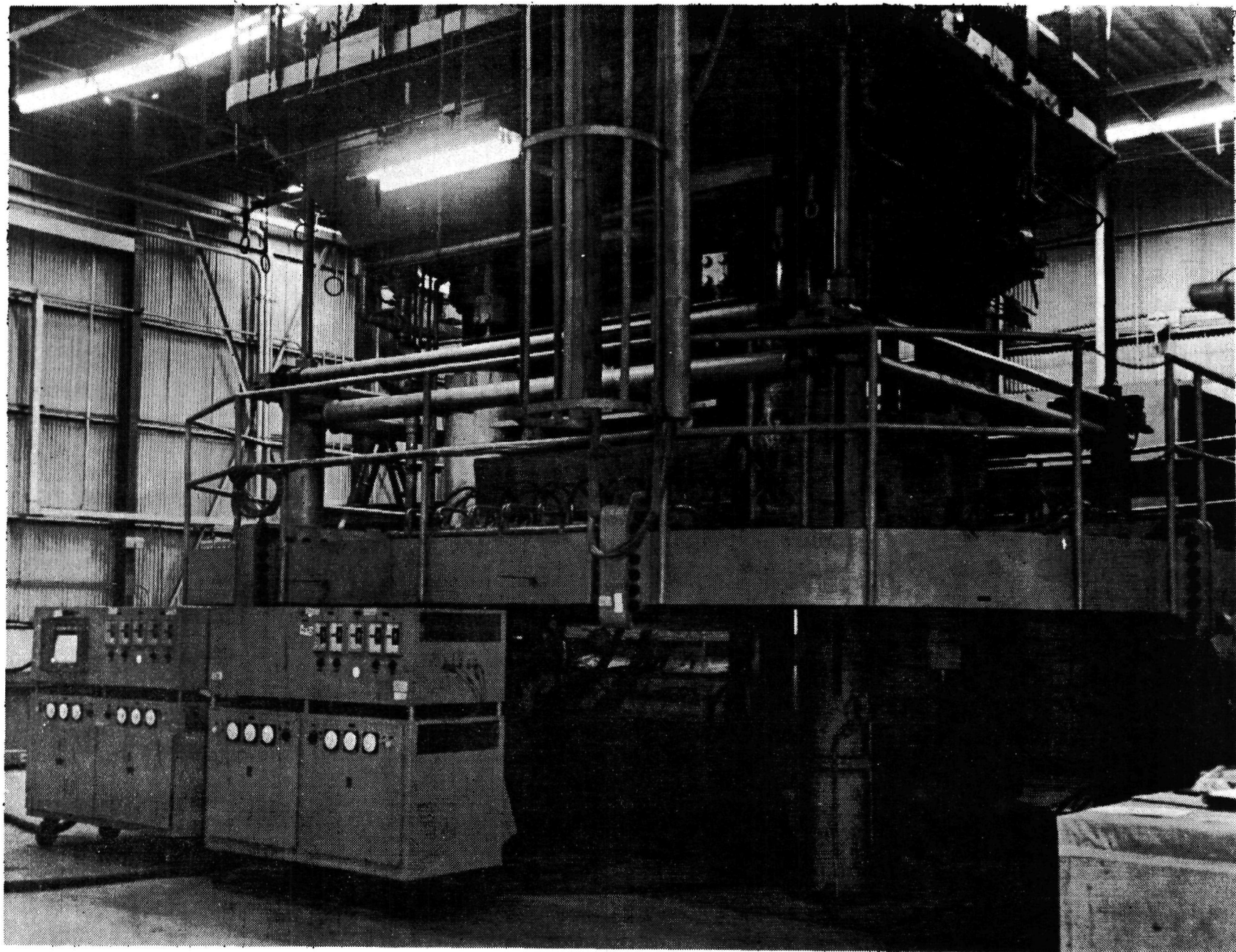


Figure 58 SPF/DB Cycle in 4500 Ton Hydraulic Press

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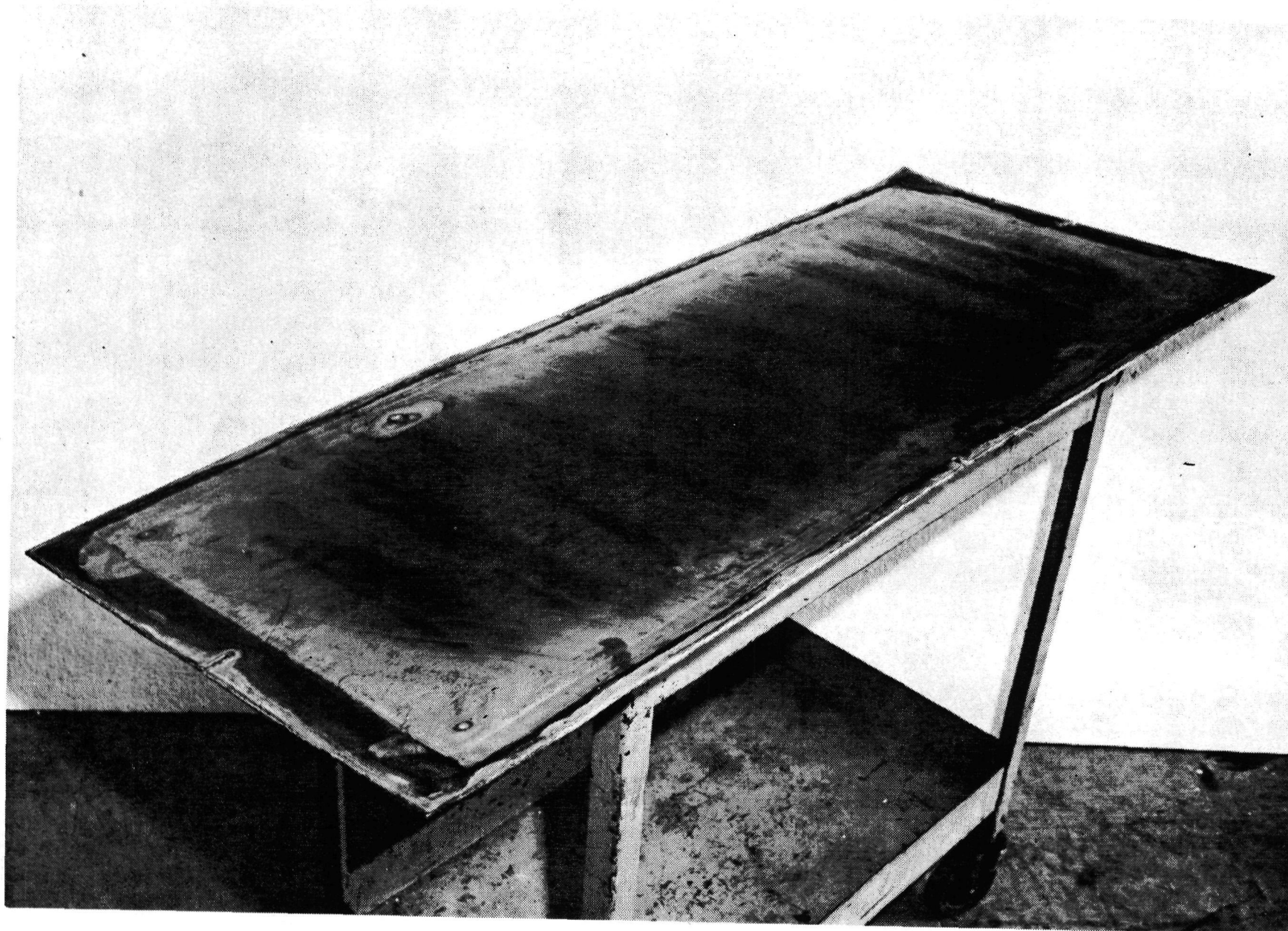


Figure 59 Feasibility Panel (Moldline Surface) After Removal from Die.

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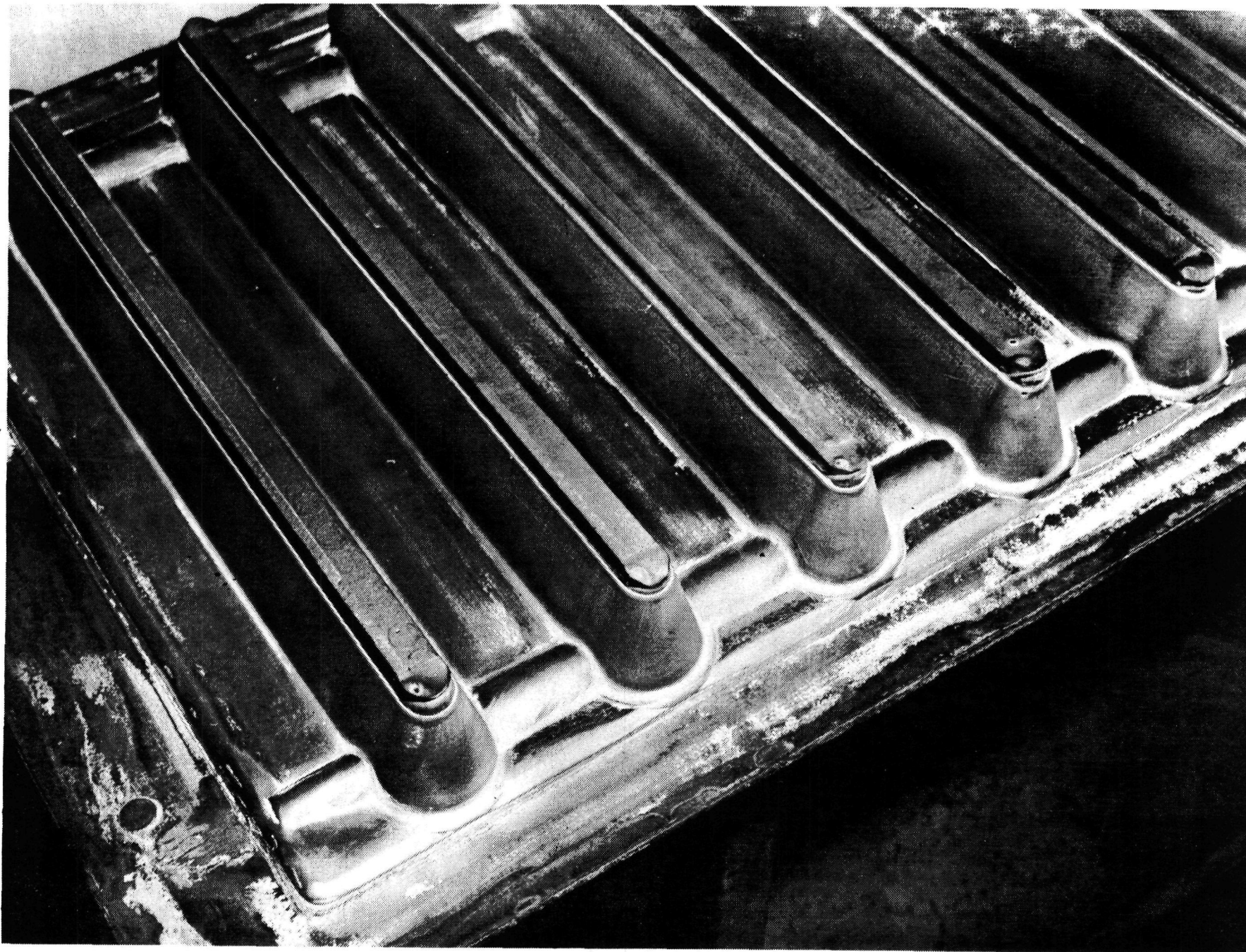
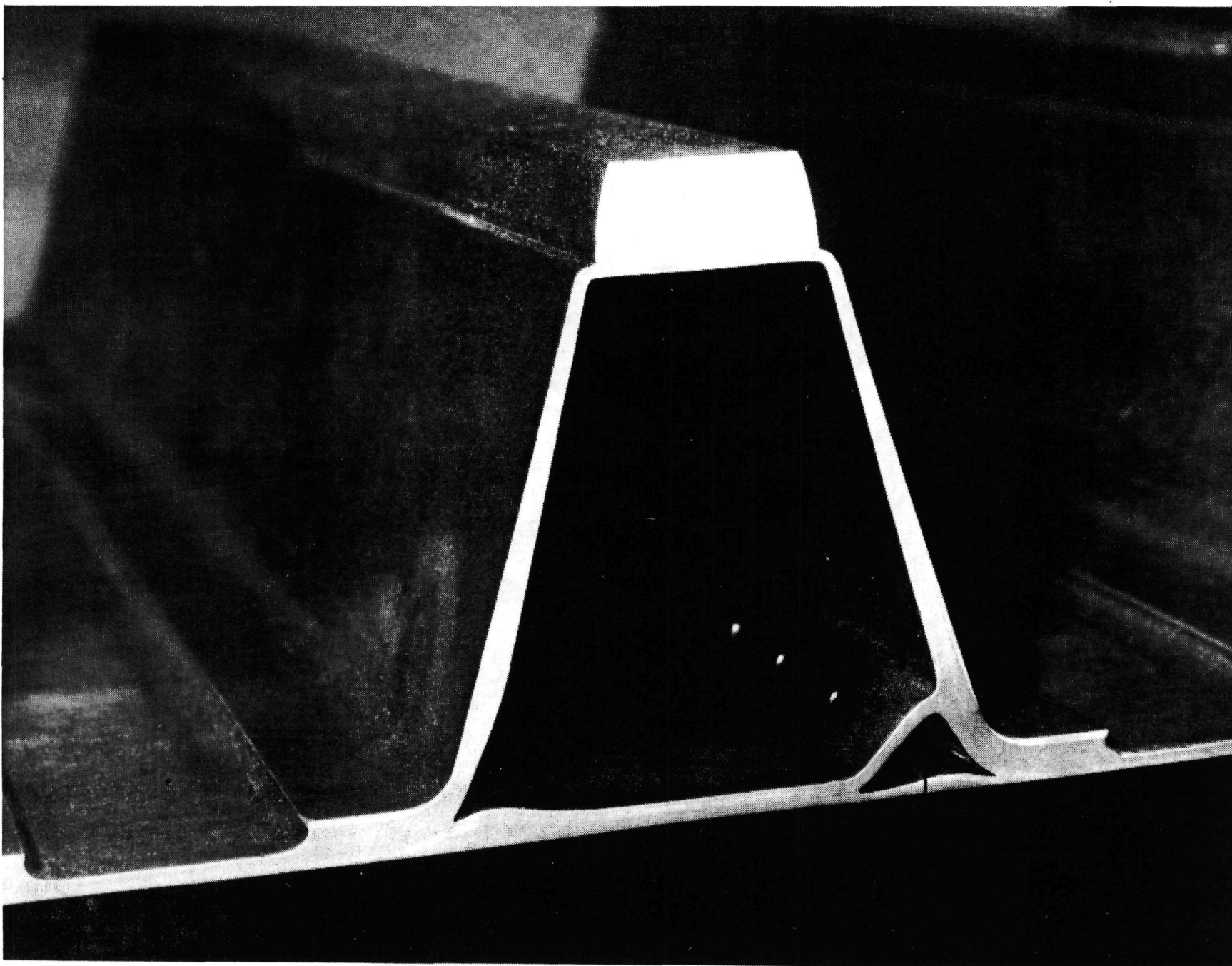


Figure 60 Feasibility Panel (Inner Surface) After Removal from Die



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Figure 61

Plenum and Metering Holes in Feasibility Panel

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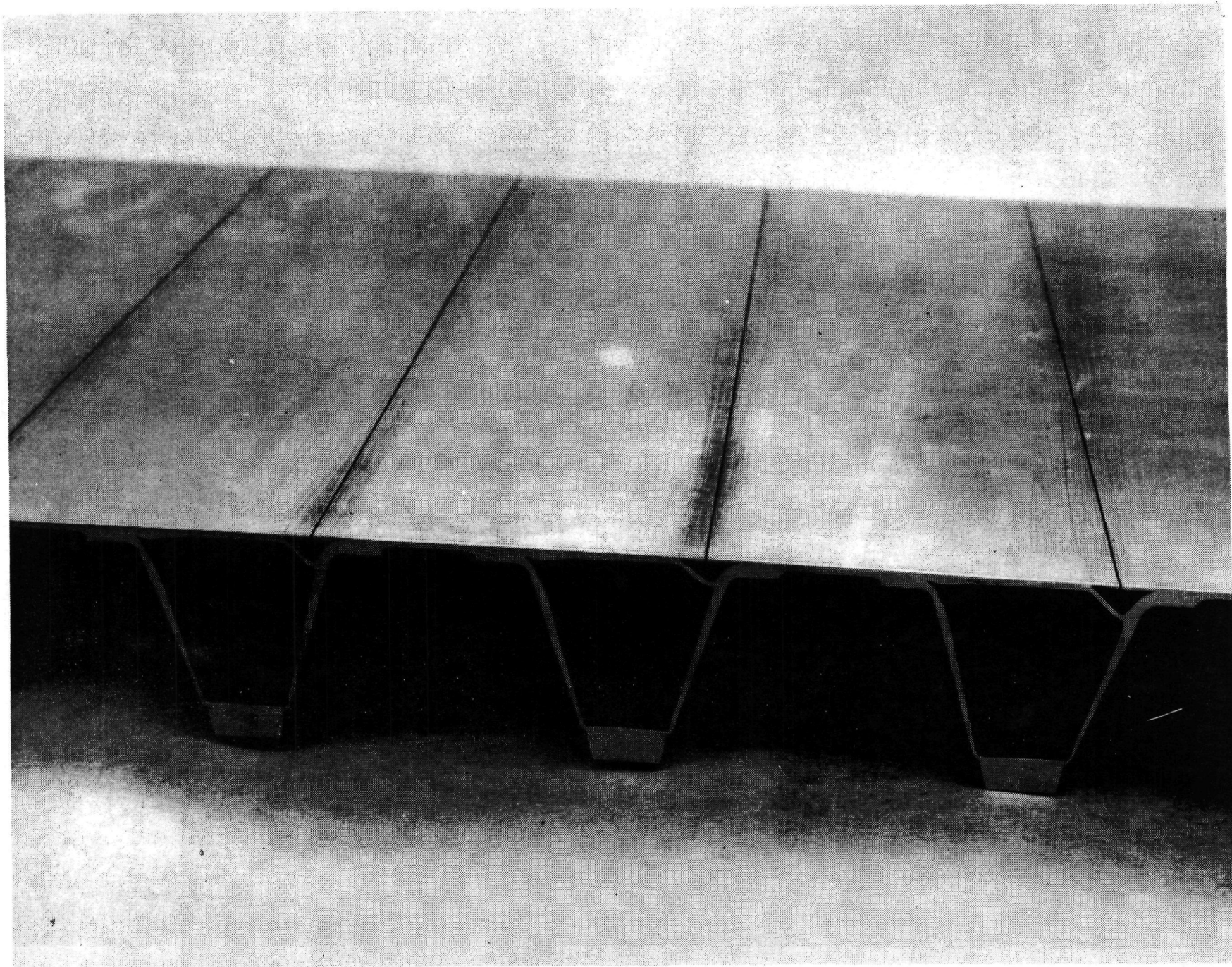
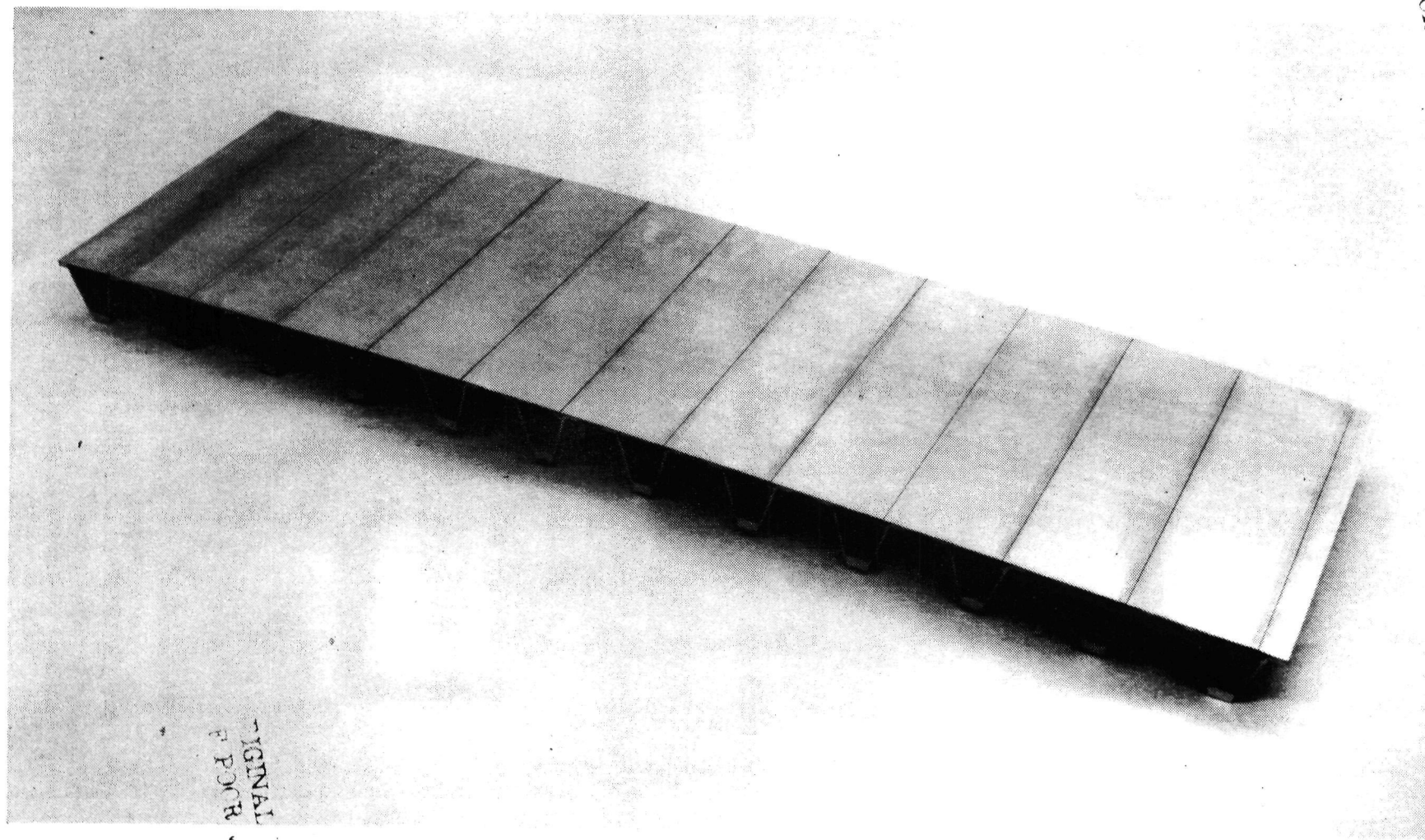


Figure 62

EDM Slotted Panel



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Figure 63

Feasibility Panel, Moldline Surface

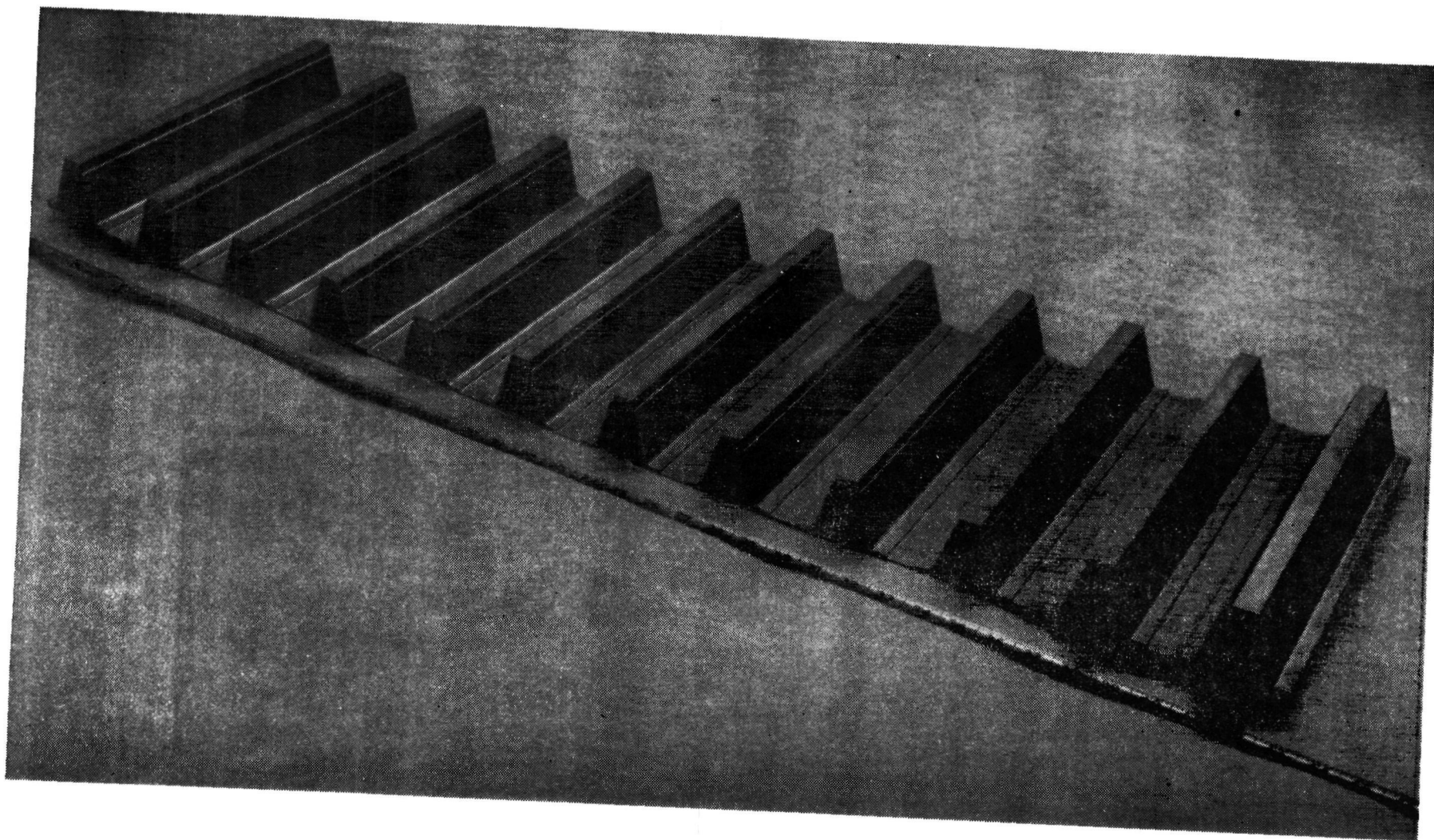


Figure 64 Feasibility Panel, Inner Surface

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OF PORT GARDNER

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OF ROCK QUALITY

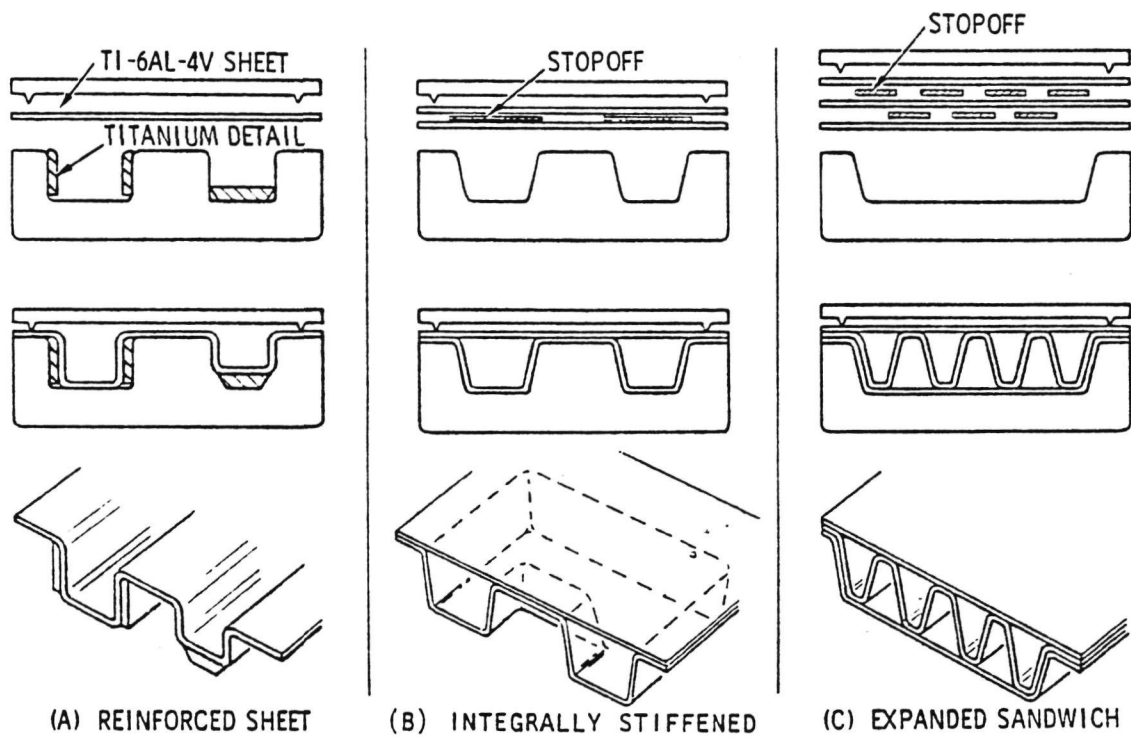


Figure A-1 Three Basic Types of SPF/DB Structure

C-2

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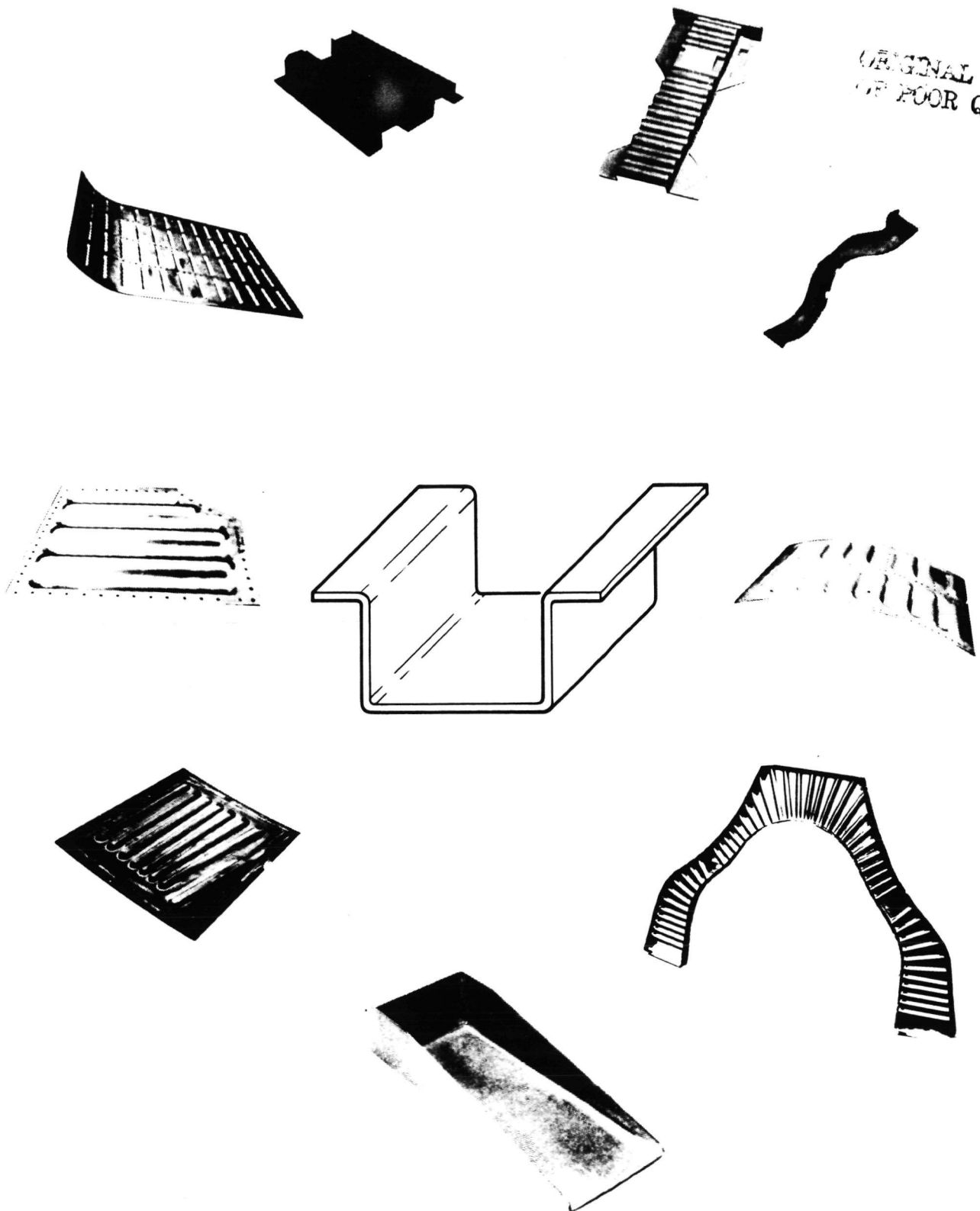


Figure A-2. Typical Variations Produced From a Basic Channel

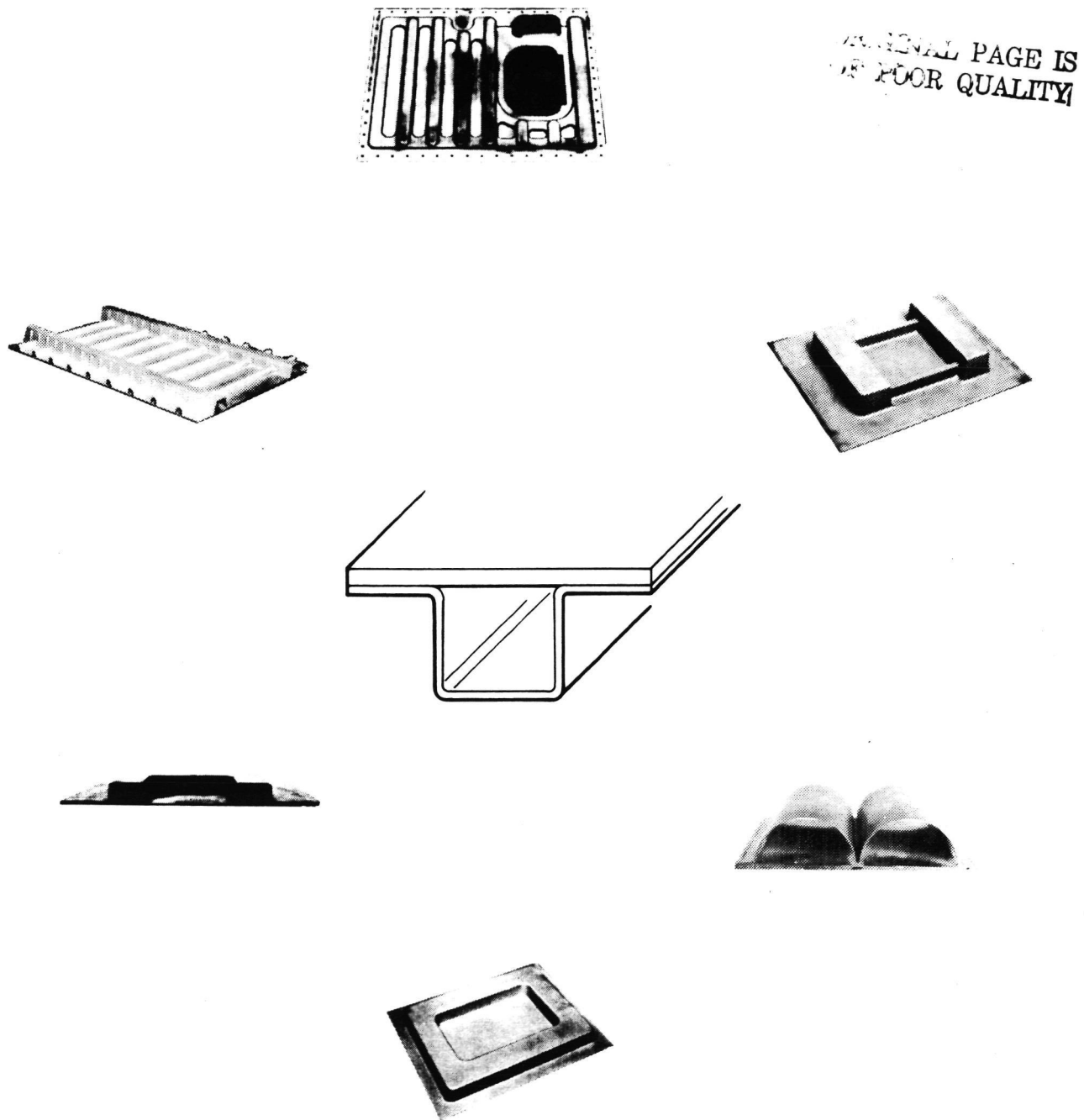


Figure A-3. Two-Sheet Technology Fabrication Variations

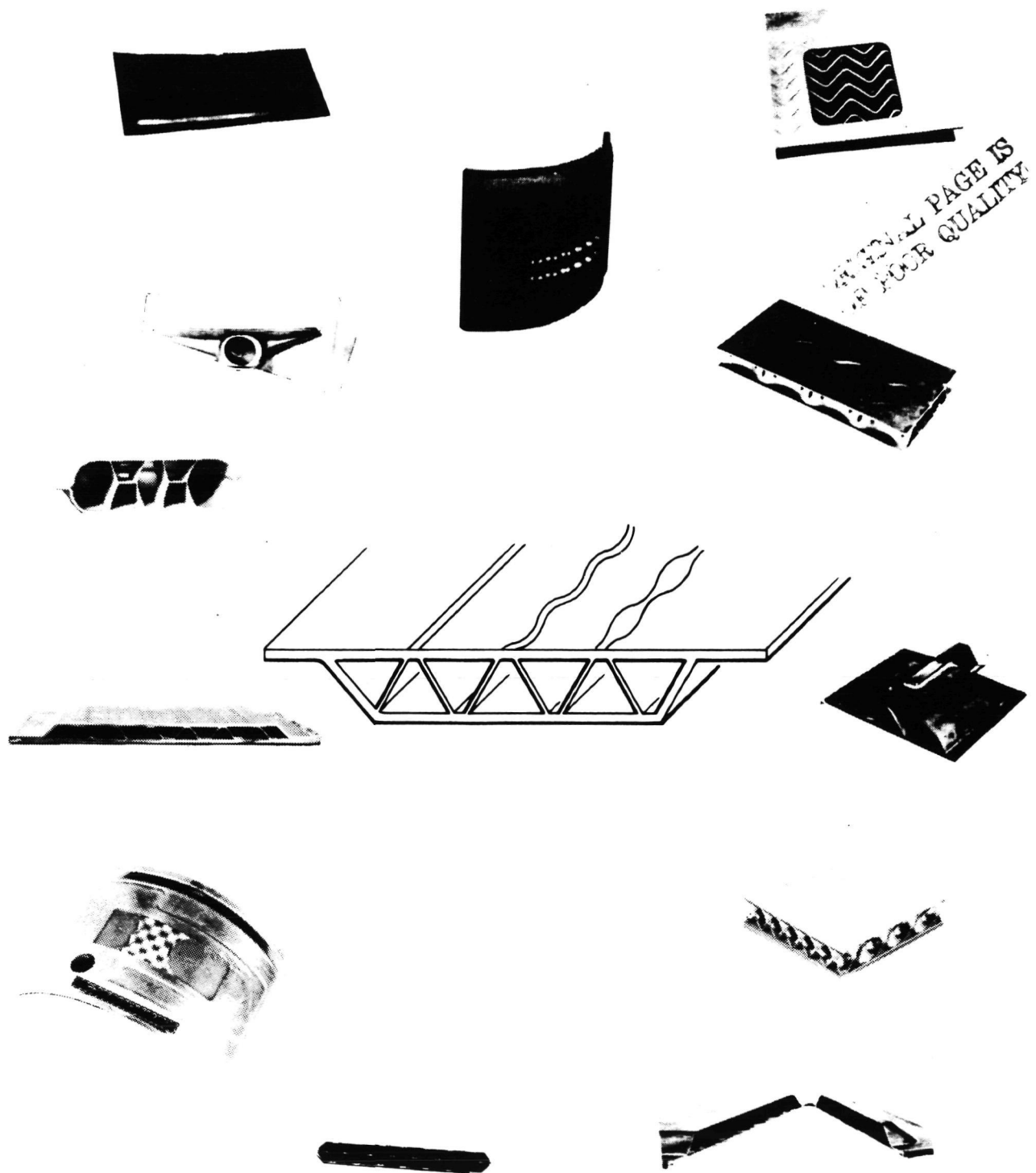


Figure A-4. SPF/DB Sandwich Variations